European Astroparticle Physics

Status and Vision

Christian Spiering, DESY

Open Symposium
European Strategy Preparatory Group
Krakow, Sept. 11, 2012

http://www.aspera-eu.org

1. Overview ASPERA Roadmap
2. Large underground detectors
3. Dark matter searches
   a. WIMPs
   b. Axions
4. Mass and nature of neutrinos: $0\nu\beta\beta$
5. Cosmic ray physics and the LHC

http://www.aspera-eu.org

1

Overview ASPERA Roadmap

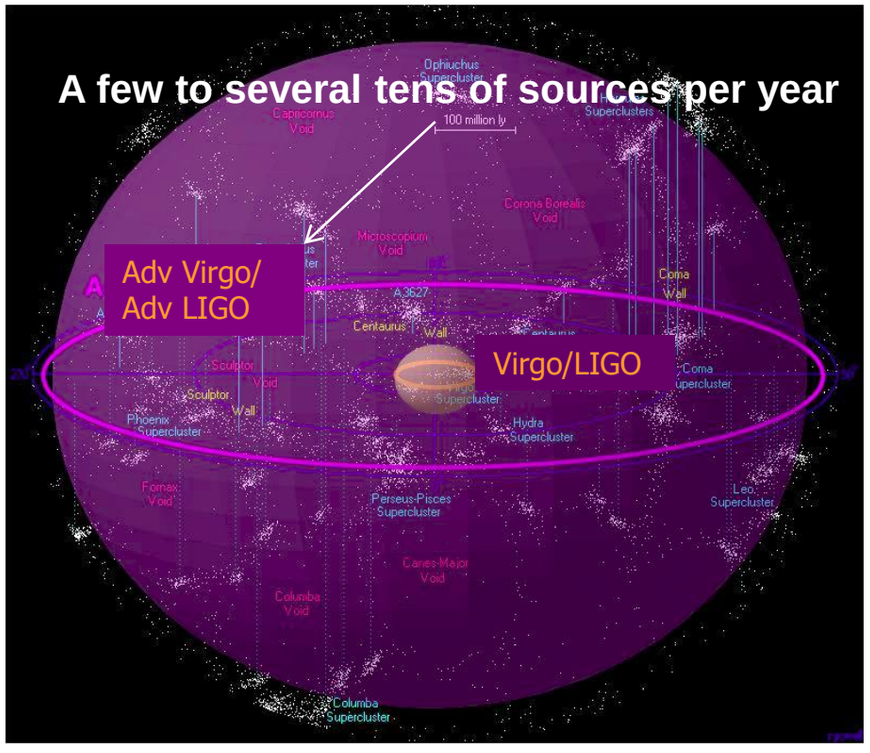
Three categories:

- Medium scale, ongoing/extension
- Large scale (few hundred M€), mid of decade
- Very large scale (several hundred M€ to G€), end of decade

http://www.aspera-eu.org

Medium scale

- Advanced detectors for gravitational waves
  - discovery in next 5 years highly probable
  - Entirely new window to Universe



- Dark Matter → see below
- Neutrino properties → see below
- Support Underground Labs (urgent: LSM extension!)

"We prioritize these projects for immediate funding, and urge agencies to join their forces for an effective, substantial support"

- impressing momentum which needs to be maintained;
- enter a region with high discovery potential;
- hand in hand with LHC physics;
- technologically ready and worldwide community

ApPEC
ASPERA Astroparticle Physics for Europe

Large scale, mid of decade

- TeV gamma-ray astrophysics: CTA
  - worldwide priority project of gamma astronomy
  - ~200M€, 2 sites (N/S), start construction 2014

- High energy neutrinos: KM3NeT
  - See the talk on oscillations and IceCube/PINGU & KM3NeT/ORCA

- High energy cosmic rays: 30,000 km² ground based array
  - Closely related to fixed target and LHC physics, see below

- Low energy neutrinos & p-decay: LAGUNA
  - → see below
  - Somewhere between category 2 and 3

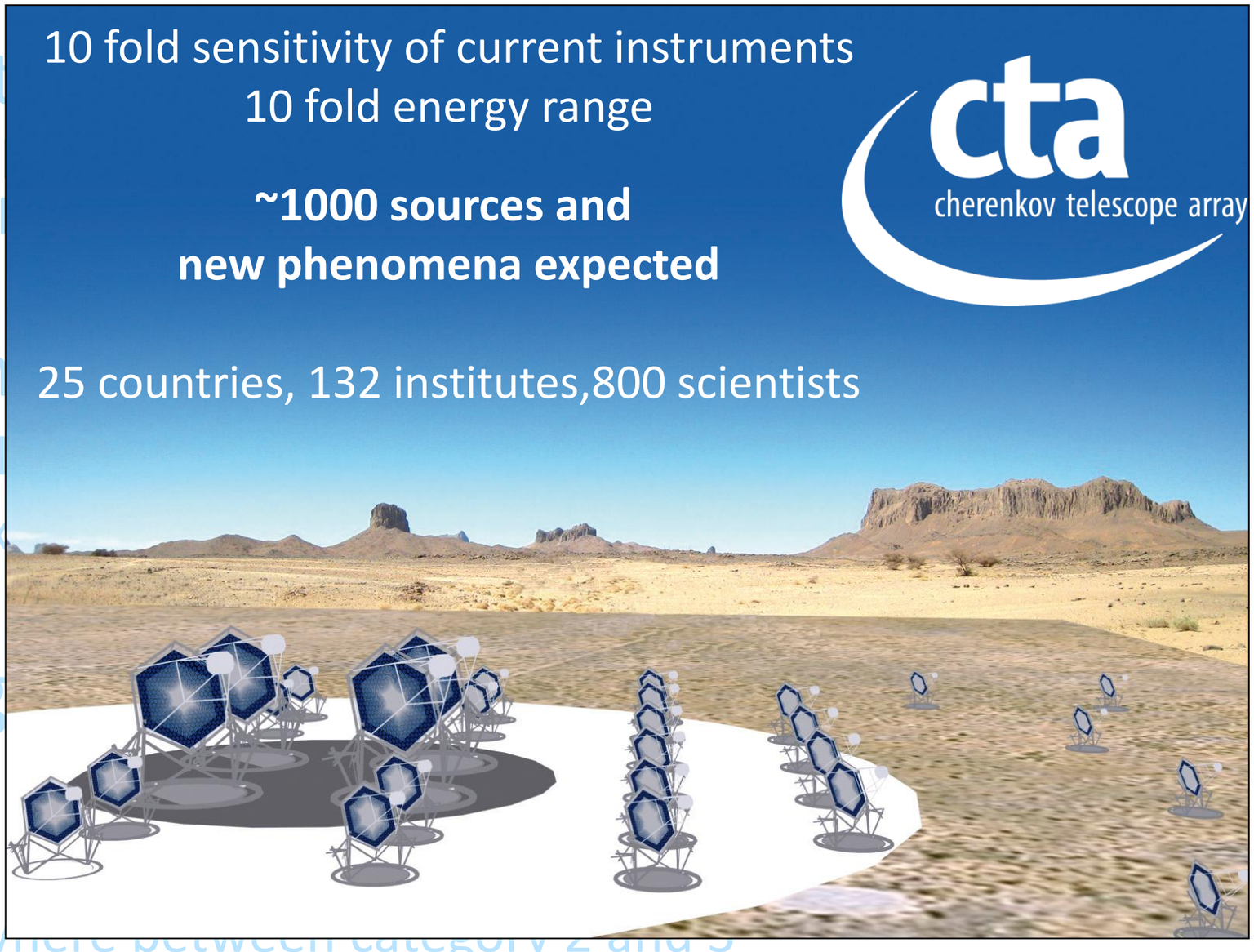
Large scale, mid of decade

- TeV gamma-ray astrophysics: CTA
  - worldwide priority project of gamma astronomy
  - ~200M€, 2 sites (N/S), start construction 2014

- High energy neut
  - See the talk on oscil
    IceCube/PINGU & K

- High energy cosm
  30,000 km² grou
  - Closely related to fix

- Low energ
  LAGUNA
  - → see
  - Somewhere between category 2 and 3



ApPEC
ASPERA Astroparticle Physics for Europe

Large scale, mid of decade

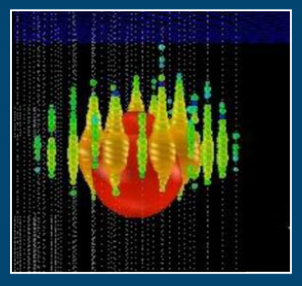
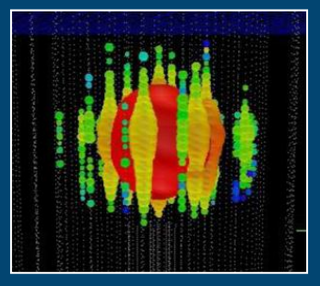
- TeV gamma-ray astrophysics: CTA
  - worldwide priority project of gamma astronomy
  - ~200M€, 2 sites (N/S), start construction 2014
- High energy neutrinos: KM3NeT
  - See the talk on oscillations and IceCube/PINGU & KM3NeT/ORCA
- High energy cosmic rays: 30,000 km² ground based array
  - Closely related to fixed target and LHC physics, see below
    - Low energy neutrinos & p-decay: LAGUNA
      - → see below
      - Somewhere between category 2 and 3

ApPEC
ASPERA Astroparticle Physics for Europe

Large scale, mid of decade

- TeV gamma-ray astrophysics: CTA
  - worldwide priority project of gamma astronomy
  - ~200M€, 2 sites (N/S), start construction 2014
- High energy neutrinos: KM3NeT
  - See the talk on oscillations and IceCube/PINGU & KM3NeT/ORCA

- **IceCube providing data with unprecedented quality and statistics!**

2 events with 1-2 PeV energy

First extraterrestrial high-energy neutrinos?

- **Strong scientific case for a Northern detector, but with substantially larger sensitivity than IceCube.**
- **Pool resources in single design for a large research infrastructure. ~250 M€**
- **Start of construction in 2014 (~40 M€ available).**
- **IceCube, ANTARES /KM3NeT, GVD-Baikal → future Global Neutrino Observatory.**

Large scale, mid of decade

- TeV gamma-ray astrophysics: CTA
  - worldwide priority project of gamma astronom
  - ~200M€, 2 sites (N/S), start construction 2014
- High energy neutrinos: KM3NeT
  - See the talk on oscillations and IceCube/PINGU & KM3NeT/ORCA
- High energy cosmic rays: 30,000 km² ground based array
  - Closely related to fixed target and LHC physics, see below
- Low energy neutrinos & p-decay: LAGUNA
  - → see below
  - Somewhere between category 2 and 3

- **Understanding the high-energy Universe**
- **Sources of cosmic rays**
- Indirect dark matter search
- Exotic particle physics
- Test basic physics principles

Very large scale, 2020 horizon

LAGUNA-type infrastructure including beam would fall in this category (see the talks of next session)

- Next generation Dark Energy surveys
  - LSST at ground
  - EUCLID in space
- Next generation graviational wave antennas
  - Einstein Telescope ET underground
  - eLISA/NGO in space

2

Neutrino Astrophysics, Neutrino Physics and Search for Proton Decay with Deep Underground Detectors

http://www.aspera-eu.org

Physics case

- **Proton decay**
  - Test further classes of SUSY models with tenfold sensitivity
- **Galactic Supernova**
  - Bonanza for astrophysics and particle physics
  - Incredibly detailed information on early SN phase and explosion mechanism
- **Solar neutrinos: details of solar model with percent accuracy**
  - Metallicity problem ← ν from **CNO** cycle → burning of heavy stars
  - Time variations on the 10^{-3} level
  - Transition vacuum/matter oscillations
- **Geoneutrinos**
  - What generates the heat of the Earth (about 30-50% due to U/Th decays).
  - How much U, how much Th? Crust, mantel? (Reactor inside Earth?)
- **Diffuse background of past Supernova**
  - „average“ SN spectrum, star formation rate, „failed“ supernova
- **Indirect dark matter search**
- Oscillation physics: see talks of Hernandez, Zito and Hagner, …

Astroparticle Physics for Europe

LAGUNA

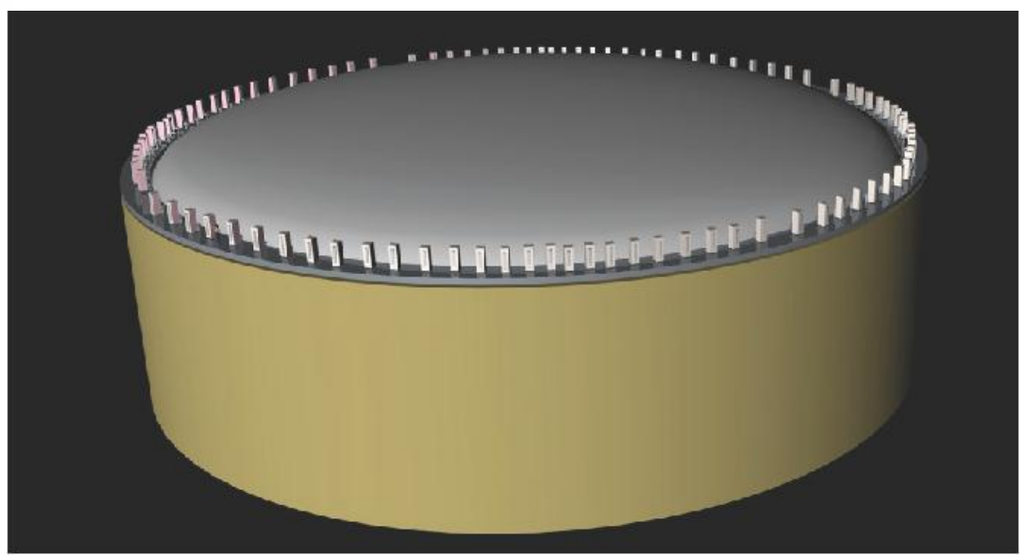
MEMPHYS

600 kton water

LENA

50 kt scintillator

50 m



GLACIER

100 kton liquid argon

*Physics potential of the 3 types of detectors for proton decay and neutrino astrophysics **

Topics	GLACIER (50 kt)	LENA (50 kt)	MEMPHYS (500 kt)
proton decay, sensitivity(10 years) $e^+\pi^0$ anti-ν K^+ (**)	 2.5×10^{34} 5×10^{34}	 - 4×10^{34}	 15×10^{34} 2.5×10^{34}
SN at 10 kpc, # events CC NC ES Elastic scatt. P	 ~ 19,500 0.8×10^4 (ν_e) 1.1×10^4 0.4×10^3 (e) -	 ~16,000 1.3×10^4 (anti-ν_e) 1.0×10^3 6.2×10^2 (e) 2.6×10^3 (p)	 ~250,000 2.5×10^5 (anti-ν_e) - 1.3×10^3 (e) -
Diffuse SN #Signal/Background events (10 years)	~50/30	~60/10	~120/100 (1 module with Gd)
Solar neutrinos # events, 1 year	^{8}B ES : 1.5×10^4 Abs: 0.5×10^5 (dependent on the achievable threshold)	^{7}Be: 3.6×10^6 pep: 1.0×10^5 ^{8}B: 2.9×10^4 CNO: 7×10^4	^{8}B ES: 1.2×10^5
Atmospheric ν # events, 1 year	5×10^3	5×10^3	5×10^4
Geo-neutrinos # events, 1 year	Below threshold	1.5×10^3	Below threshold

* some numbers strongly depend on model assumptions and give a qualitative rather than an exact quantitative comparison.
** this channel is particularly prominent in SUSY theories. Indications for SUSY at the LHC would boost its importance.

*Physics potential of the 3 types of detectors for proton decay and neutrino astrophysics **

Topics	GLACIER (50 kt)	LENA (50 kt)	MEMPHYS (500 kt)
proton decay, sensitivity(10 years)			
$e^+\pi^0$	2.5×10^{34}	-	15×10^{34}
anti-ν K^+ (**)	5×10^{34}	4×10^{34}	2.5×10^{34}
SN at 10 kpc, # events	~~19,500~~	~16,000	~250,000
CC	0.8×10^4 (ν_e)	1.3×10^4 (anti-ν_e)	2.5×10^3 (anti-ν_e)
NC	1.1×10^4	1.0×10^3	-
ES	0.4×10^3 (e)	6.2×10^2 (e)	1.3×10^3 (e)
Elastic scatt. P	-	2.6×10^3 (p)	-
Diffuse SN #Signal/Background events (10 years)	~50/30	~60/10	~120/100 (1 module with Gd)
Solar neutrinos # events, 1 year	^{8}B ES : 1.5×10^4 Abs: 0.5×10^5 (dependent on the achievable threshold)	^{7}Be: 3.6×10^6 pep: 1.0×10^5 ^{8}B: 2.9×10^4 CNO: 7×10^4	^{8}B ES: 1.2×10^5
Atmospheric ν # events, 1 year	5×10^3	5×10^3	5×10^4
Geo-neutrinos # events, 1 year	Below threshold	1.5×10^3	Below threshold

Low energy!

* some numbers strongly depend on model assumptions and give a qualitative rather than an exact quantitative comparison.
** this channel is particularly prominent in SUSY theories. Indications for SUSY at the LHC would boost its importance.

ApPEC
ASPERA Astroparticle Physics for Europe

Recommendation: large underground detectors

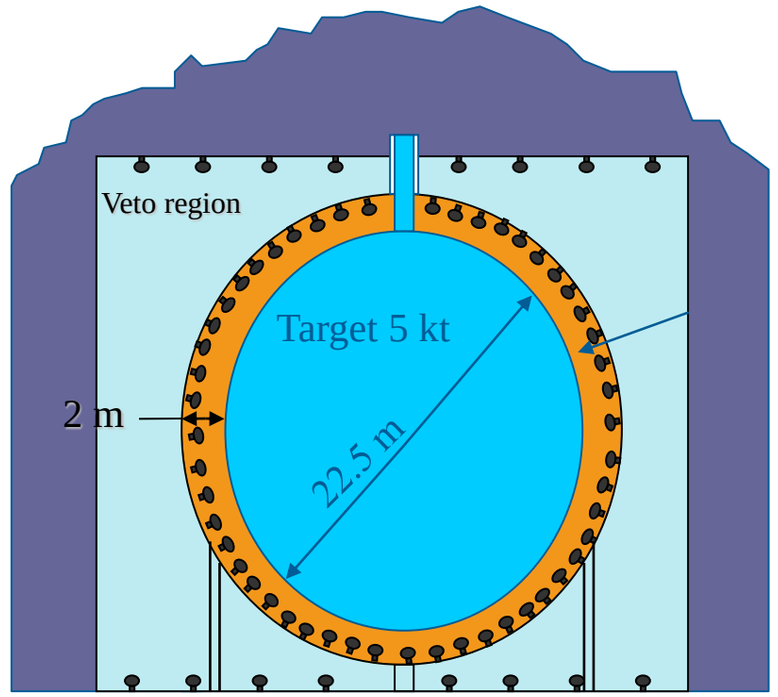
The SAC notes the high costs for the creation of underground laboratories on the one hand, and the unique capabilities of large neutrino detectors in particle physics (proton decay) and astroparticle physics (supernova, solar neutrinos, dark matter, geo-neutrinos) on the other hand. The SAC concludes that the **program with neutrino beams must be flanked by a strong astroparticle program to justify the high investment.** It is important to note that **the astroparticle physics topics will be the decision driver for a good part of the community and that therefore the astroparticle physics potential of different options should be considered when examining the overall coherence of a global program.** There is an opportunity for a common program on both accelerator based neutrino physics and astro-particle physics that will have **more impact than the sum of its parts**. We recommend therefore that:

- **CERN and the national agencies, as well as ApPEC**, should support a vigorous **R&D program on neutrino detectors (e.g. liquid argon) and beam design studies (e.g. a neutrino beam to Pyhäsalmi), in anticipation of a critical decision in 2015**.
- **ApPEC supports the astroparticle physics program** that will profit from the synergy with the accelerator-based program (e.g. **a liquid scintillation detector in Pyhäsalmi**) as well as **medium scale astroparticle physics detectors** (including feasibility studies for high-density infills of high-energy neutrino telescopes) which can in principle determine the neutrino mass hierarchy and other neutrino parameters.
- **Given the obvious worldwide interest and the high project costs, it is recommended that CERN, together with key European agencies and ApPEC, enter into discussions with their US and Asian counterparts in order to develop a coherent international strategy for this field, including relevant astroparticle physics issues.**

Large Underground Neutrino Detectors: Community Input

- #11 Conclusions of NUTURN Workshop, May 2012
- # 24: Realistic next-generation nucleon decay and neutrino expt. Capable to probe leptonic CP violation

- **# 45: Neutrino and Astroparticle Physics Program of JINR and Russian Institutes : Baksan LSc 5-50 kt**
  - 5 kt option: geo-neutrinos, solar neutrinos, SN neutrinos
  - 50 kt option: full LENA program



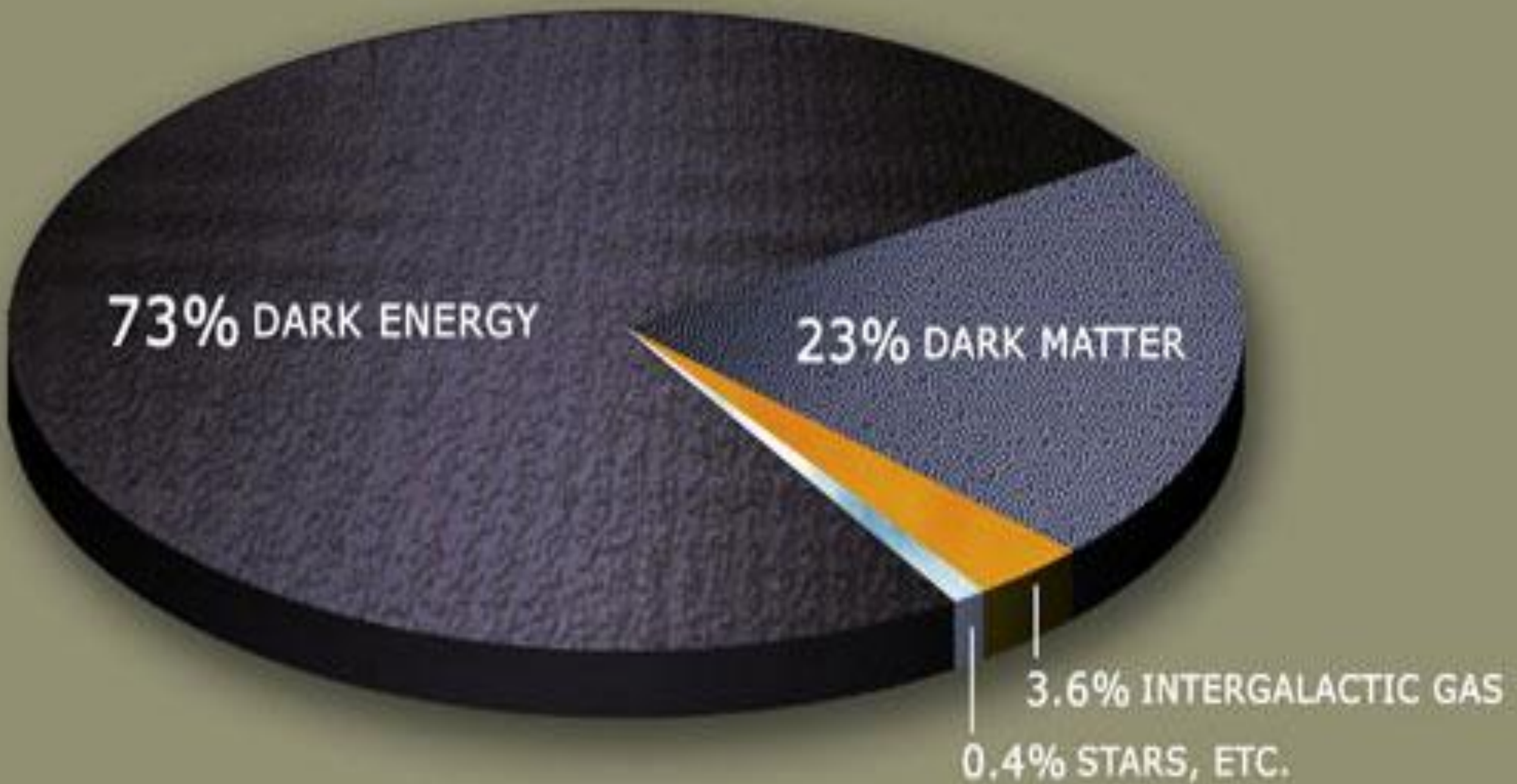
- #70: LENA
- #74 LAGUNA-LBNO: CN2PY (Cern to Pyhäsalmi): an opportunity of particle and astroparticle neutrino and GUT physics
- #86 Hyper-Kamiokande

3

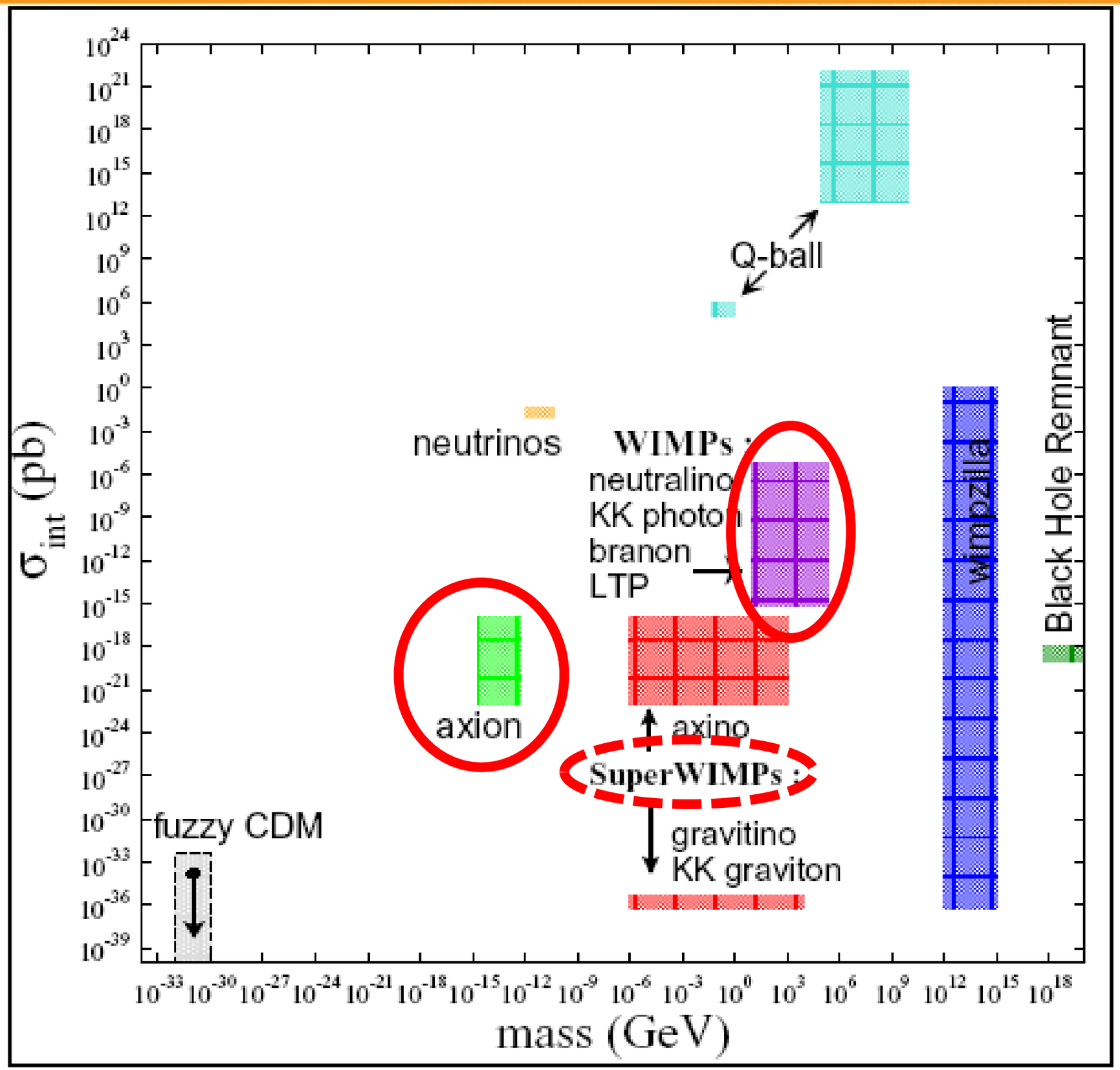
Dark Matter Searches

ApPEC
ASPERA Astroparticle Physics for Europe

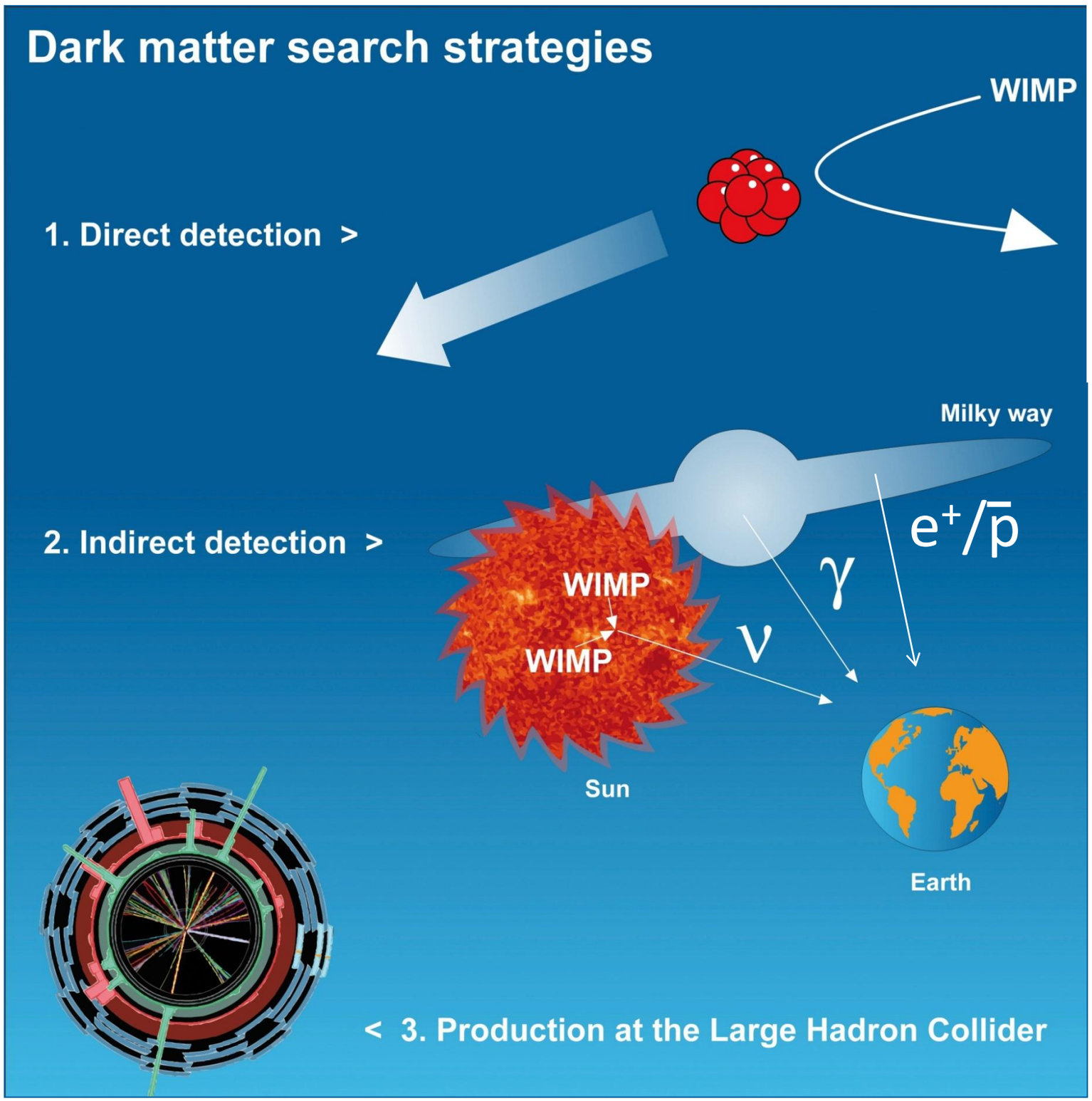
Physics case

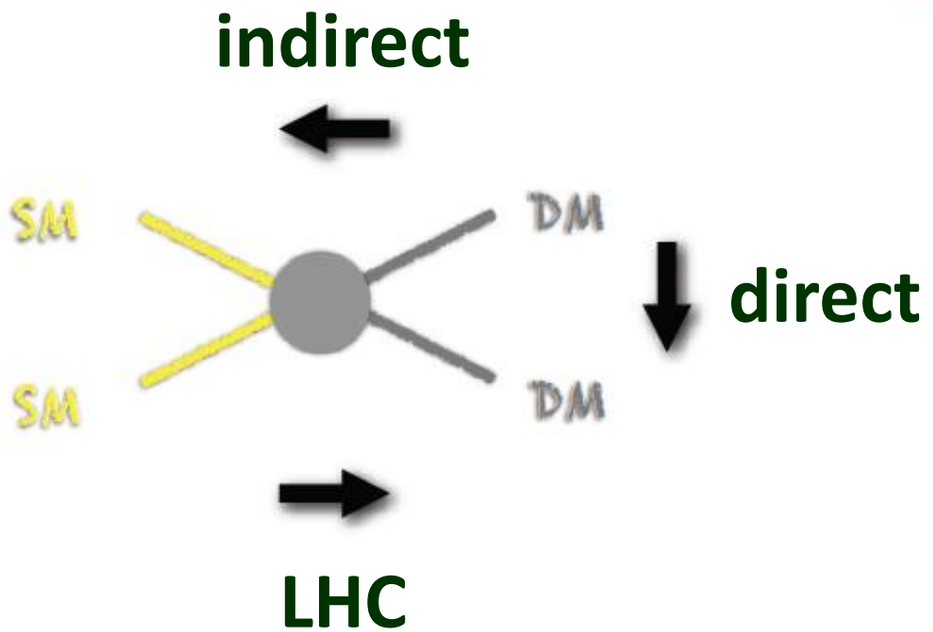


Particle Candidates



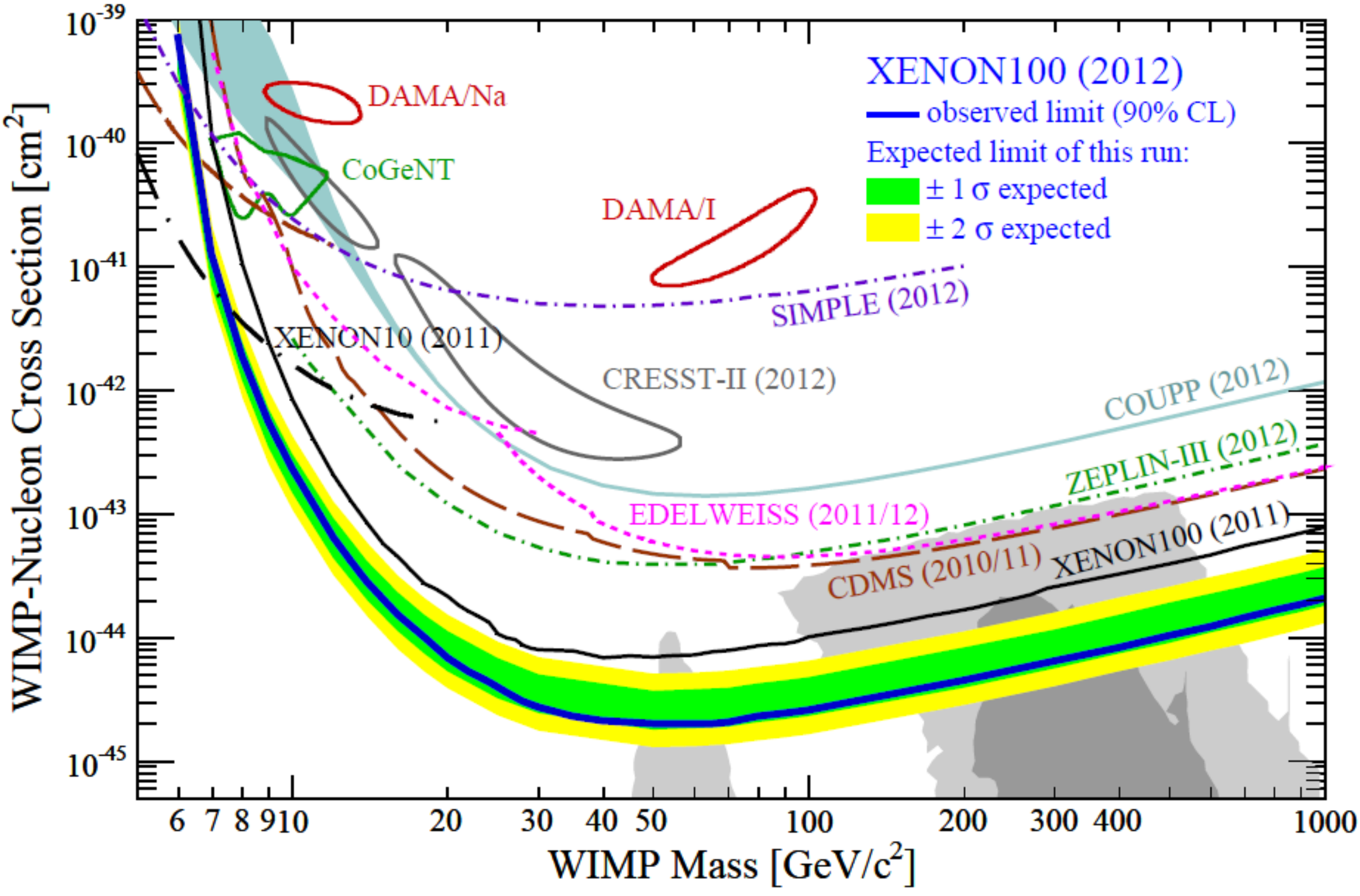
Methods to search for (SUSY) WIMPs



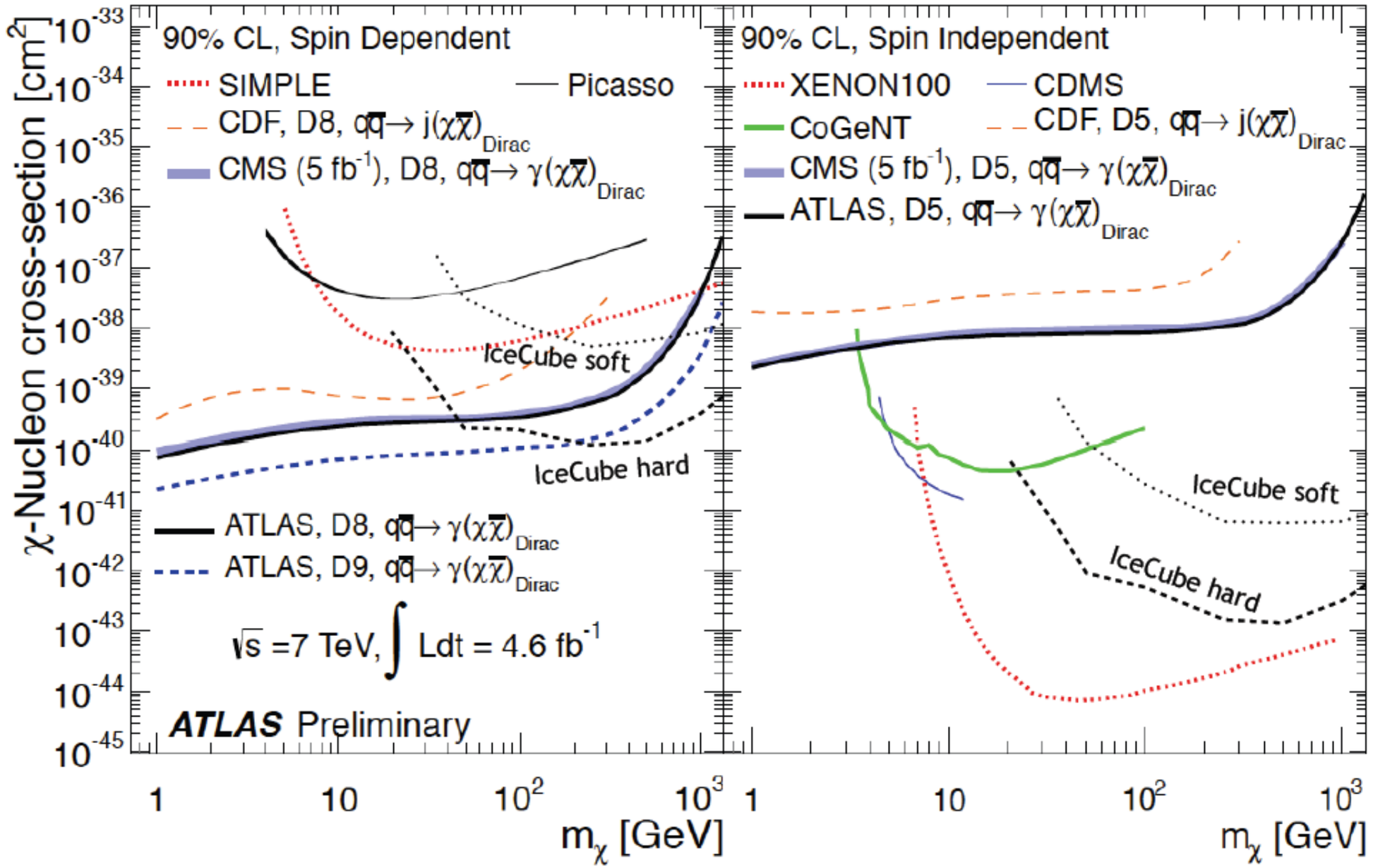


ν	IceCube, Antares
γ	HESS/MAGIC/VERITAS Agile, Fermi
e/p	balloon exp.s, Pamela, Fermi, AMS

Snapshot Summer 2012

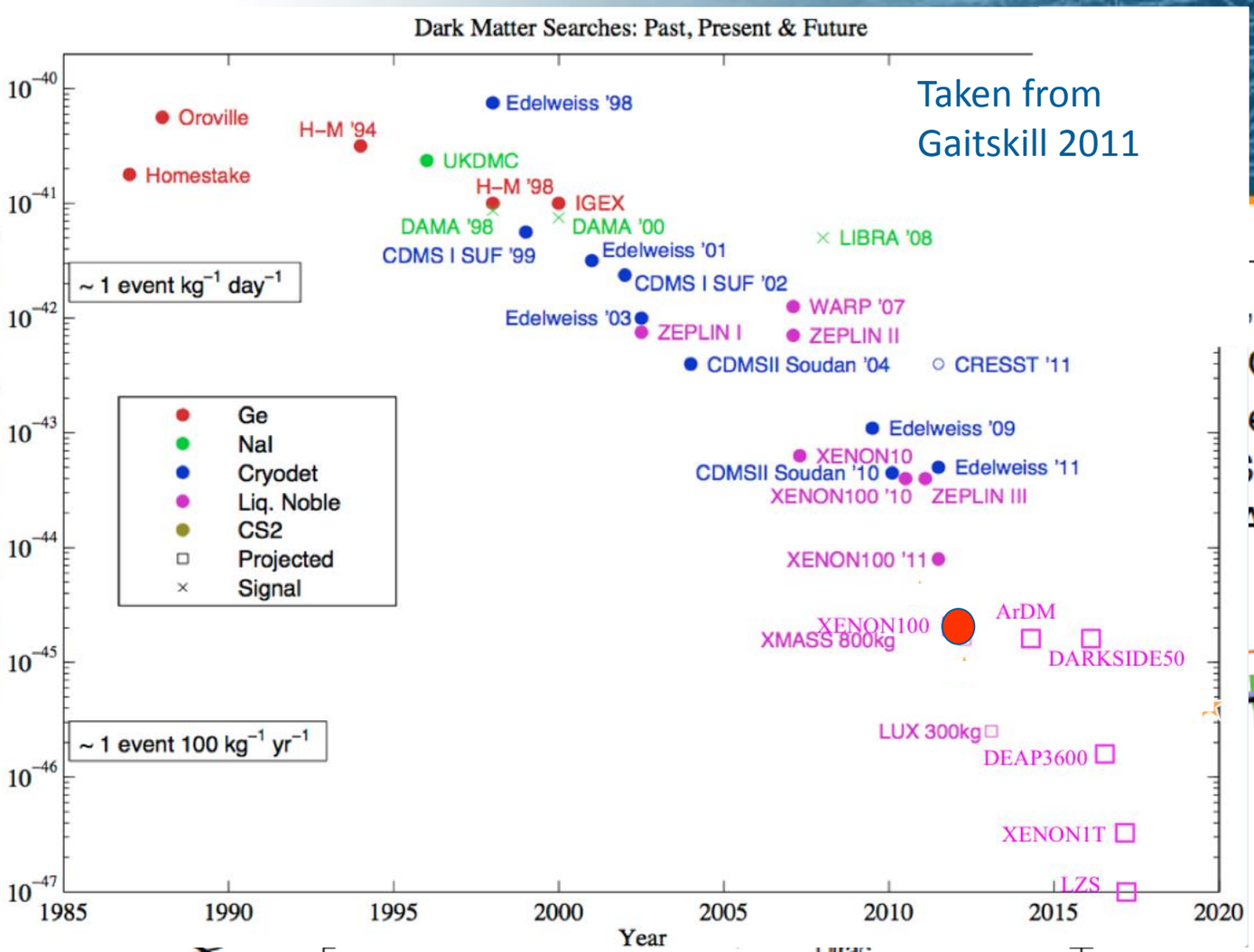


Synergy of direct, indirect and LHC searches



- **Direct searches will improve sensitivity by a factor of 100 over the next 5-7 years**
- **Indirect searches with IceCube will improve sensitivity by a factor 10-20**
- **AMS results: looking forward to data release end of the year!**
- **LHC 7 → LHC 14: factor 300-1000**

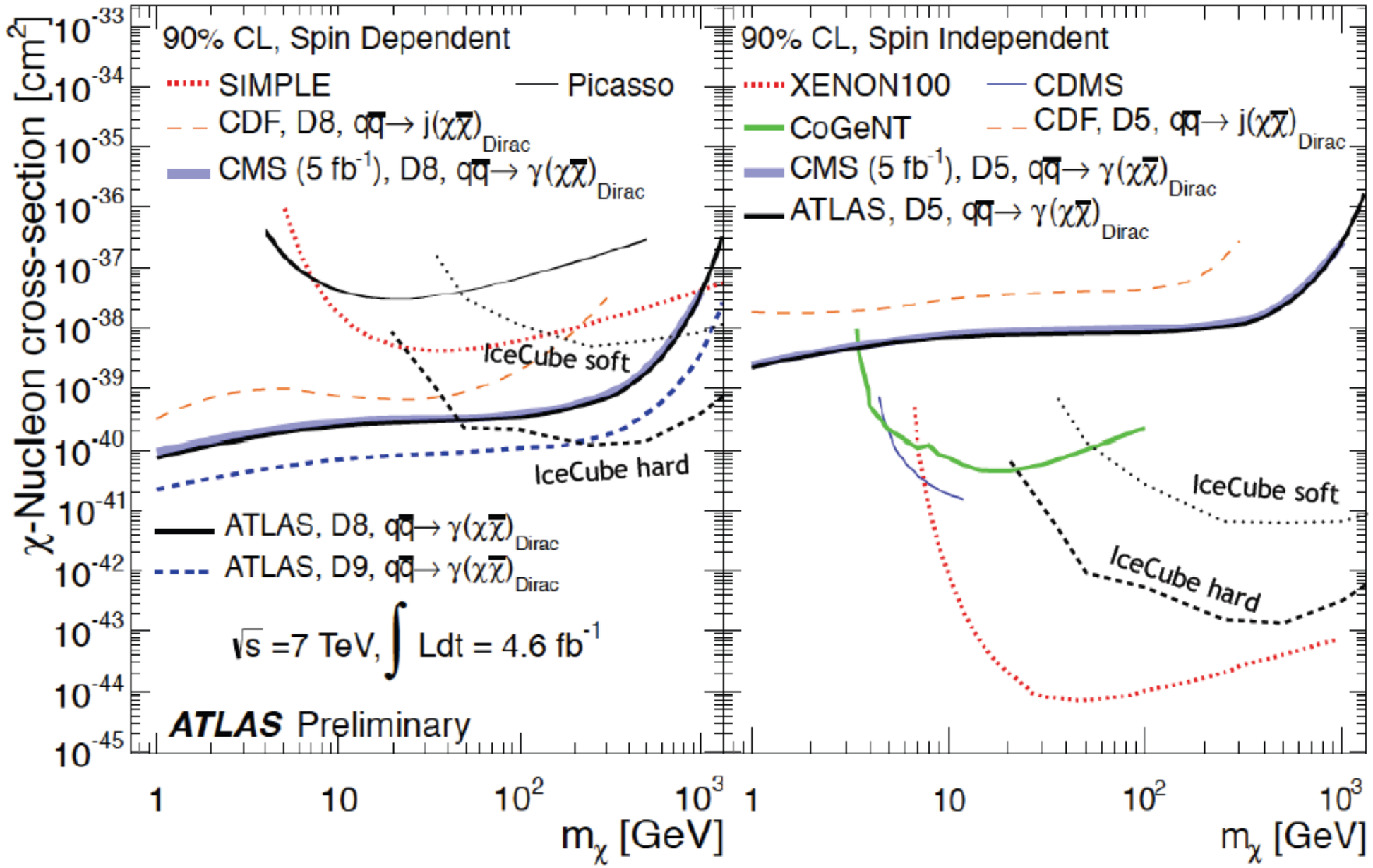
indirect and LHC searches



Taken from Gaitskill 2011

- **Direct searches will improve sensitivity by a factor of 100 over the next 5-7 years**
- **Indirect searches with IceCube will improve sensitivity by a factor 10-20**
- **AMS results: looking forward to data release end of the year!**
- **LHC 7 → LHC 14: factor 300-1000**

Synergy of direct, indirect and LHC searches



- **Direct searches will improve sensitivity by a factor of 100 over the next 5-7 years**
- **Indirect searches with IceCube will improve sensitivity by a factor 10-20**
- **AMS results: looking forward to data release end of the year!**
- **LHC 7 → LHC 14: factor 500-1000**

Recommendations WIMP Dark Matter

- **With the advent of the LHC and thanks to a new generation of astroparticle experiments using direct and indirect detection methods, the SUSY -WIMP dark matter hypothesis will be proven or disproven within the next 5-10 years.**
- Stormy progress of LXe technology. XENON100 with record limits. XENON1T under construction.
- LAr technology attracts new interest using argon depleted in ^{39}Ar. Potential of technology will be demonstrated by DarkSide-50 (50 kt, LNGS, end 2012).
- **SAC recommends that DARWIN (target mass of noble liquids up to 10-20 tons) is pursued and supported. Choice of double-target options after demonstration of LAr capabilities.**
  Other potential capabilities of DARWIN: solar ν in real time, $0\nu\beta\beta$ decay with ^{136}Xe.
- Bolometric approach remained (nearly) competitive with noble liquids in sensitivity. EDELWEISS (Ge), CRESST ($CaWO_4$). CDMS in US. Need cross-check of possible signals in noble liquids!
- **SAC supports development of EURECA (~1 ton sensitive mass) and the on-going cooperation with the CDMS follow-up projects.**
- SAC supports R&D on directional detection, as a confirmation of the galactic character of potential positive detection by high-density target detectors
- SAC supports improving DAMA/LIBRA w.r.t. lower threshold and lower background to better understand the modulation. Fully independent experiment of same/similar technology is crucial.

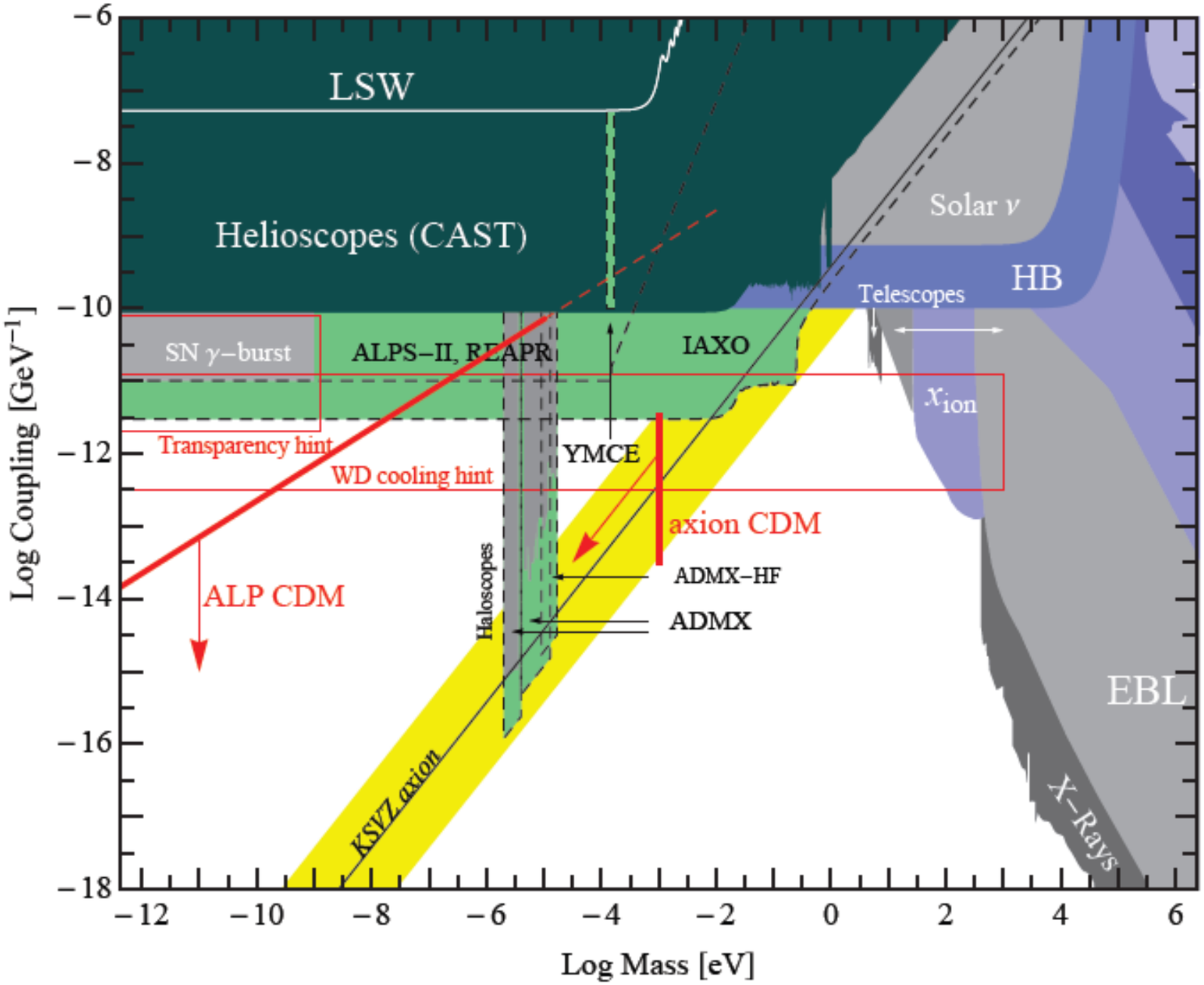
Axions

- SAC recommendations: Although not all approaches in this field are strictly related to dark matter, all have the potential for revealing new physics. A CAST follow-up is discussed as part of CERN‘s physics landscape (new magnets, new cryogenic and X-ray devices). SAC supports R&D on this followp up, as well as smaller ongoing activities on the search for axions and axion-like particles.
- Input from the community:
  Fundmental physics at low energies – the quest for axions and other new light particles

Embedding the Standard Model into more fundamental theories often predicts low mass and very weakly interacting particles, so-called WISPs (Weakly Interacting Slim Particles), such as the axion. A number of small-scale experiments at the intensity/precision frontier – for example “light shining through a wall”, haloscopes and helioscopes – are actively searching for these elusive particles, complementing searches for physics beyond the Standard Model at accelerators. A plausible next generation of experiments includes scaled-up versions of the existing techniques as well as innovative concepts, together covering a huge unexplored parameter space. A WISP discovery would have a tremendous impact on our understanding of fundamental physics, astrophysics and may shed light upon the mysteries of Dark Matter and Dark Energy.

Axions

Parameter space for axions or axion-like particles



- **Experimentally excluded**
- Astronomy constraints
- **Cosmology constraints**
- **Sensitivity of planned experiments**

IAXO: CAST follow-up

10T magnets, 16m
low-BG/threshold X-ray detectors

50-100 M€

Further community Input Dark Matter Search

Super-WIMPs

- #127 Boyarsky, Ruchayskiy, Shaposhnikov: „Searching for Dark Matter“
  - no sign of WIMPs from LHC and direct detection
  - Super-weakly interacting DM candidates (**Super-WIMPs**)
  - Detectable via decays → sharp X-ray line
  - Need X-ray spectrometer with $\Delta E/E \leq 10^{-3}$, limited imaging capabilities
  - **Such a mission will not materialize within the astrophysical community itself but requires strong support by particle physics community**

4

Mass and Nature of the Neutrino

Here: Double-Beta decay.
Direct mass measurement:
see talk of Hamish Robertson

Physics case

- **Majorana vs Dirac**
- mass & mass hierarchy

Physics beyond SM

Essential for Leptogenesis

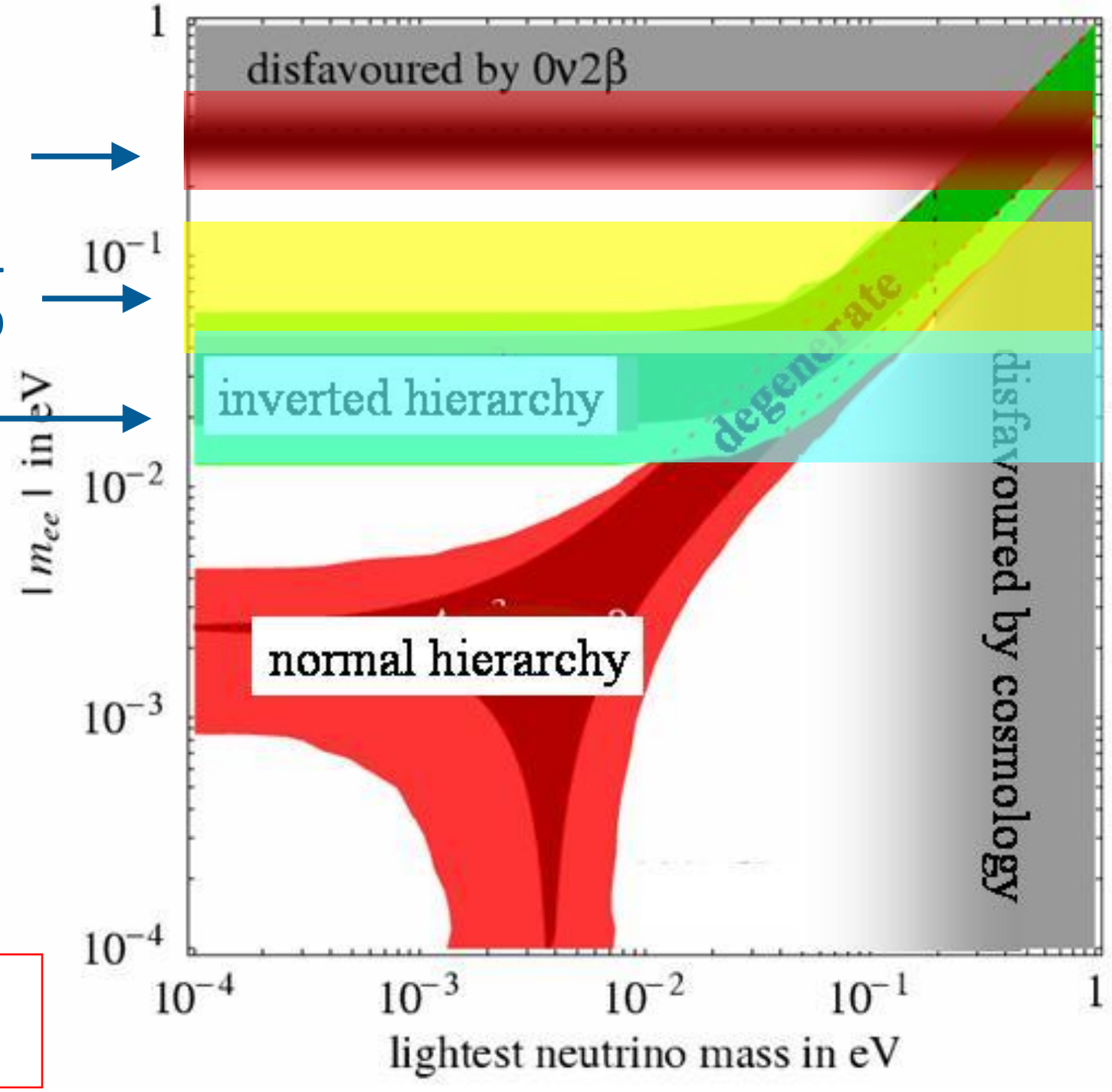
Physics case

- **Majorana vs Dirac**
- mass & mass hierarchy

KKGH claim →

GERDA, EXO200, SNO+ CUORE, SuperNEMO →

Ton-scale →



Price tag for ton-scale 50-150 M€.

Recommendations 0νββ decay

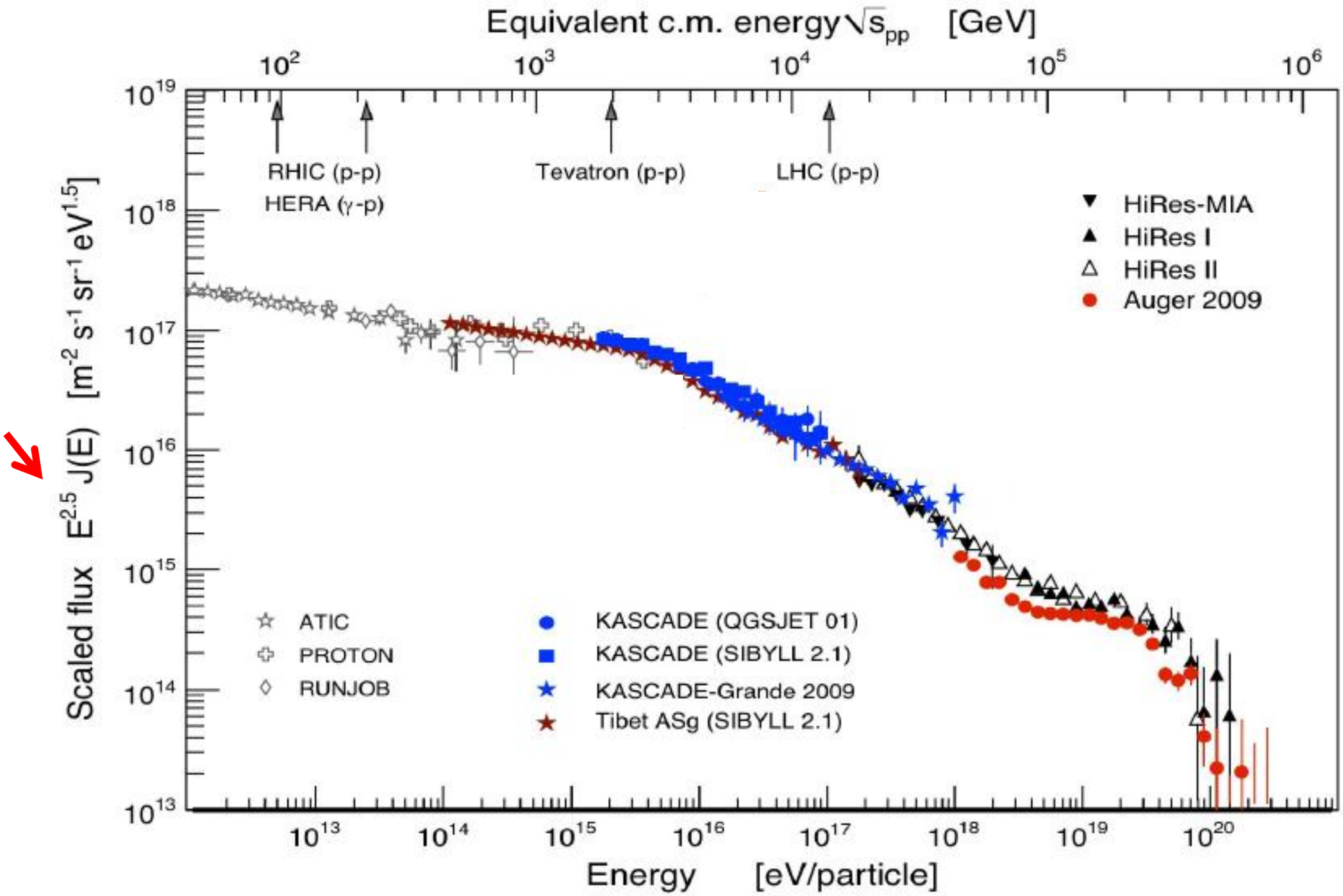
- Data taking of new generation 0νββ has started: **Kamland-Zen (**Japan), **EXO** (US), **GERDA, Cuore-0** (Europe): ***Degenerate*** region
- **CUORE** (start ≥2014) will probe part of ***Inverted Hierarchy*** region.
- Discovery on degenerate level → path to precision measurement with 3 different nuclei and the unique capabilities provided by **SuperNEMO**.
- GERDA/CUORE/SuperNEMO build on long experience and validation with precursors.
- **NEXT:** new approach, steep time gradient. SAC encourages coll. To demonstrate all aspects of technology/physics capability and to move ahead toward NEXT-100 (see input paper on NEXT).
- **SAC recommends a phased experimental approach towards ton-scale masses with a sensitivity exploring fully the mass range predicted by oscillation experiments for the Inverted Hierarchy.**
- SAC supports **R&D towards new promising technologies** (scintillating bolometers, pixel detectors, ….) in view of final assessment of most effective approach towards ton-scale
- SAC encourages companies and labs to continue R&D on new techniques for **isotope separation.**
- **High cost of ton-scale → realisation within worldwide collaborations, as e.g. pursued by GERDA and MAJORANA.**

5

Cosmic Ray Physics and the LHC

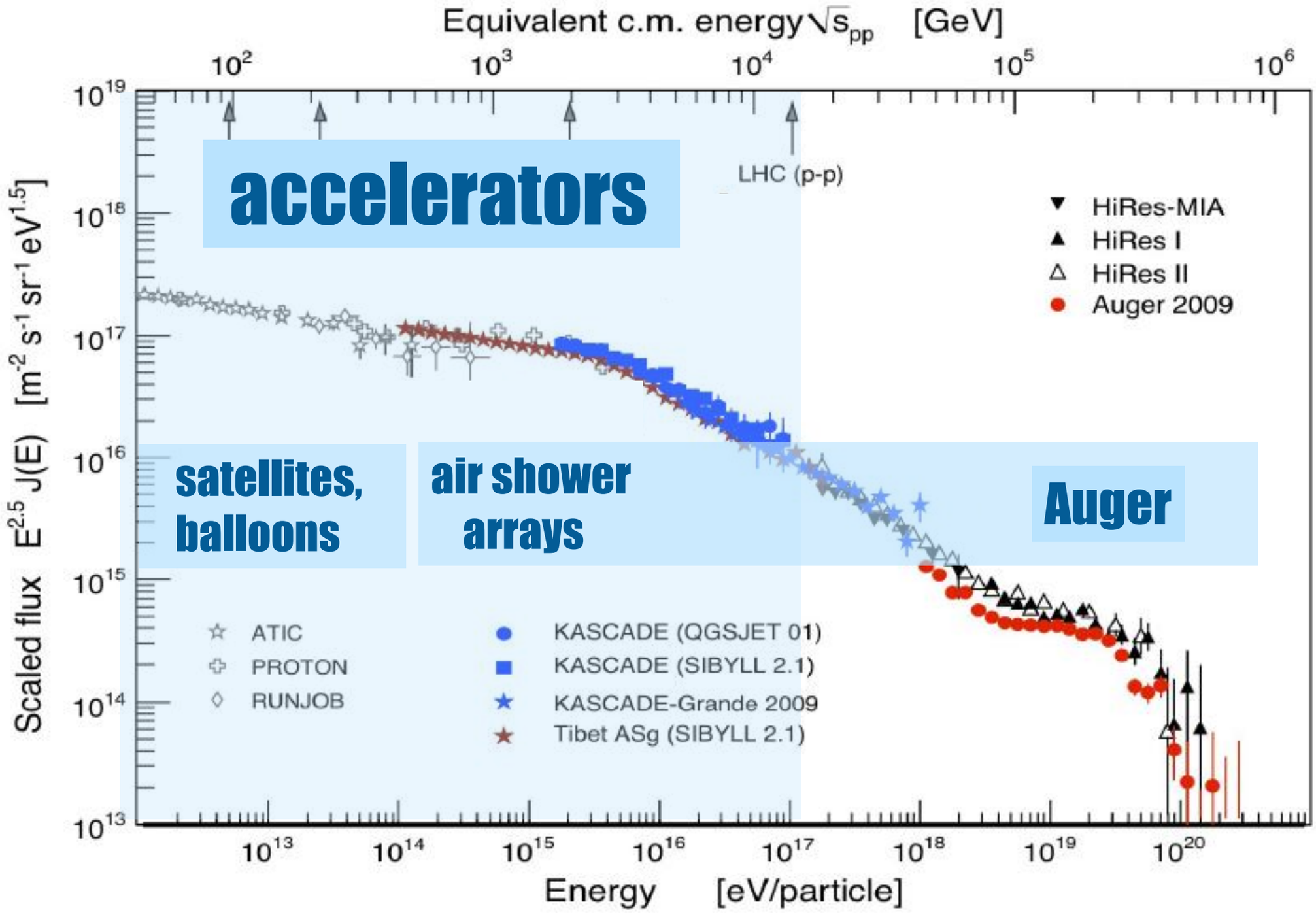
http://www.aspera-eu.org

Cosmic Rays



R. Engel (KIT)

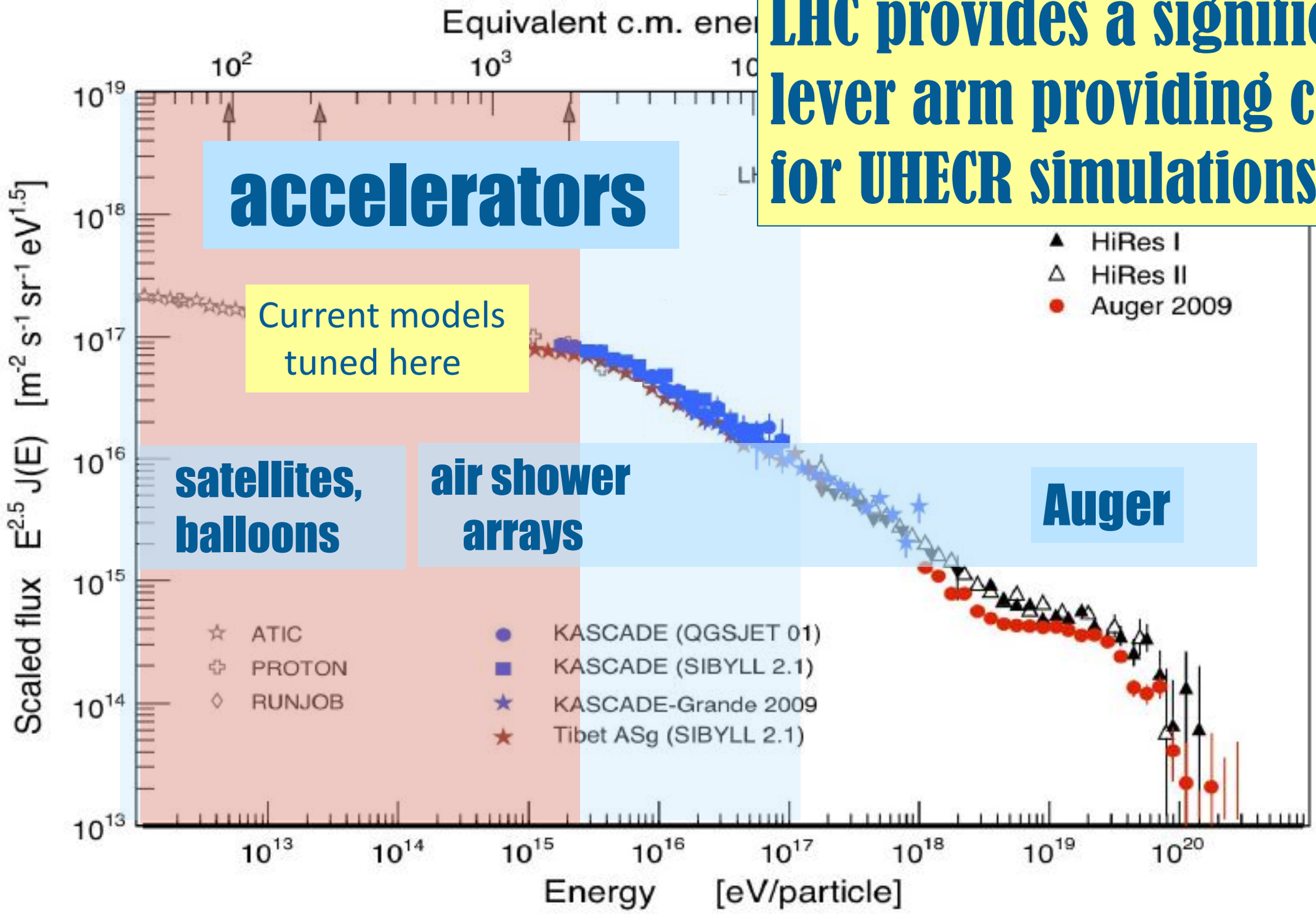
Cosmic Rays and LHC



R. Engel (KIT)

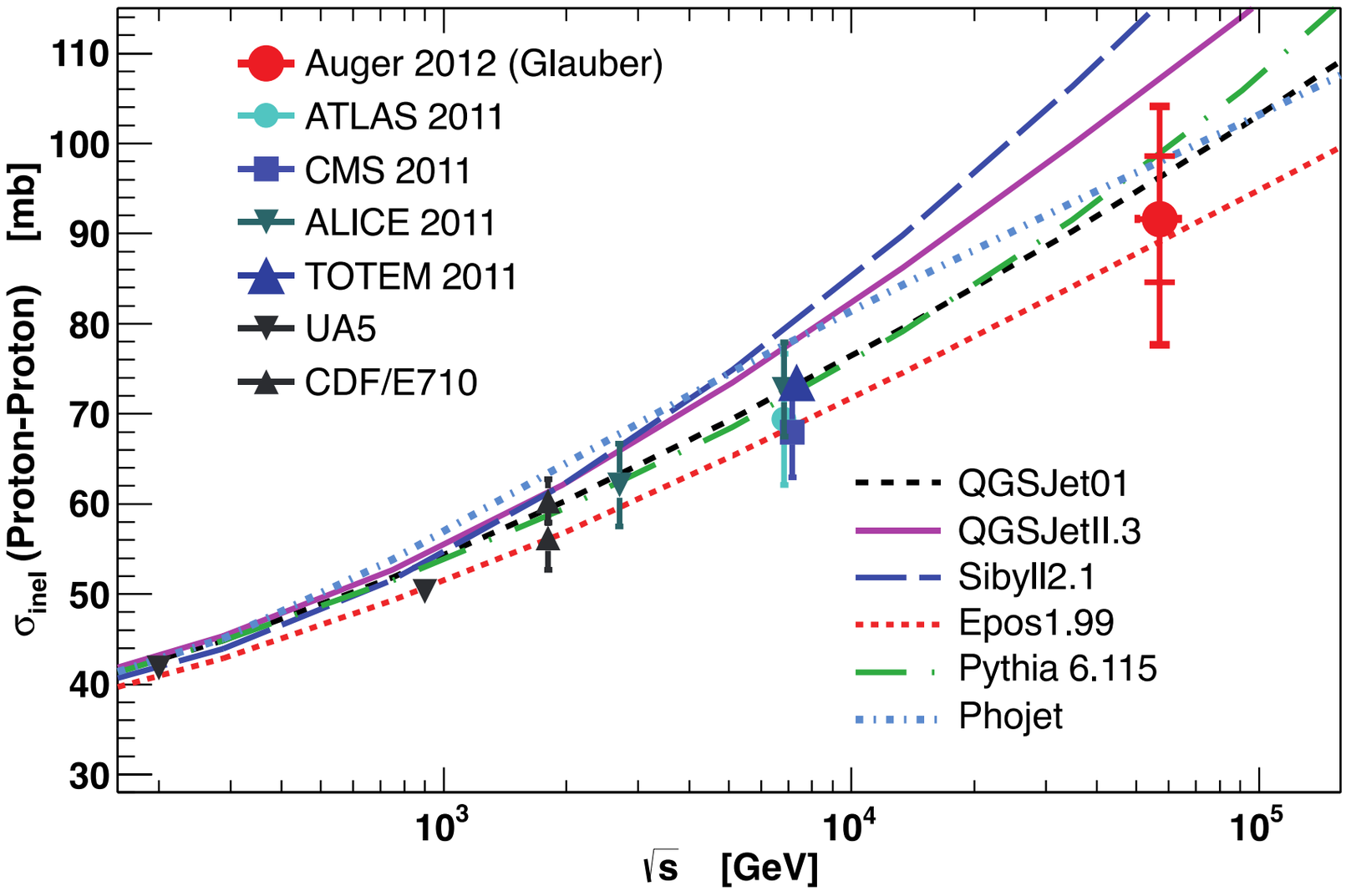
Cosmic Rays and LHC

LHC provides a significant lever arm providing constraints for UHECR simulations !



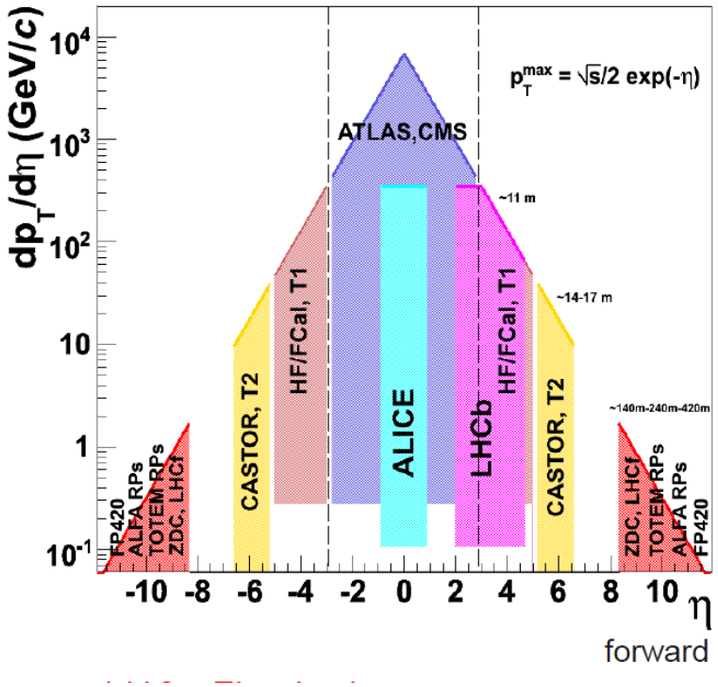
R. Engel (KIT)

pp inel. cross section at sqrt(s)=57 TeV



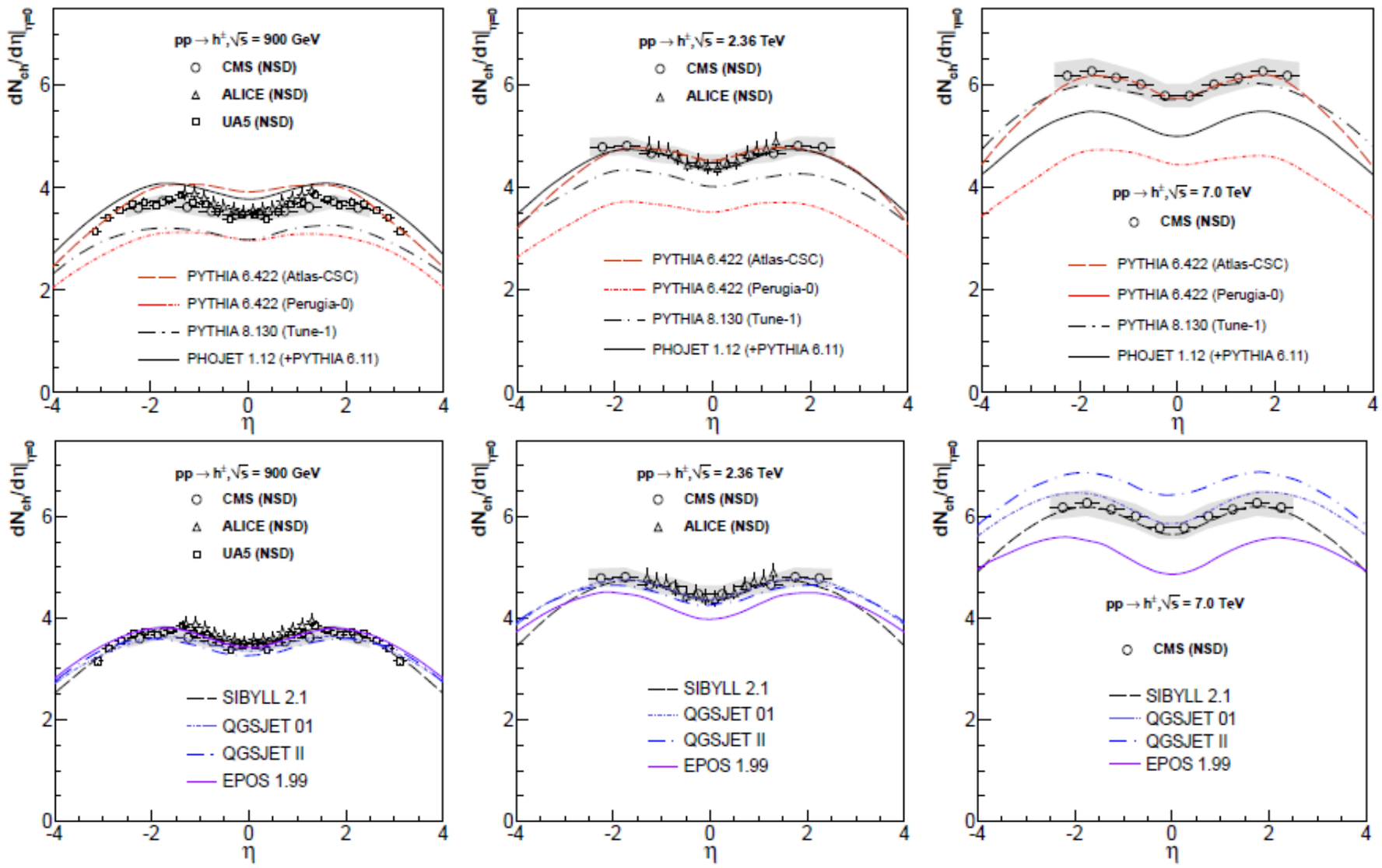
- Test Glauber model
- Tune EAS simulations

Models and data: rapidity distribution



- LHC detectors cover all wide rapidity range
- EAS models bracket accelerator data
- no model perfect, but EAS models seem to do better than HEP models

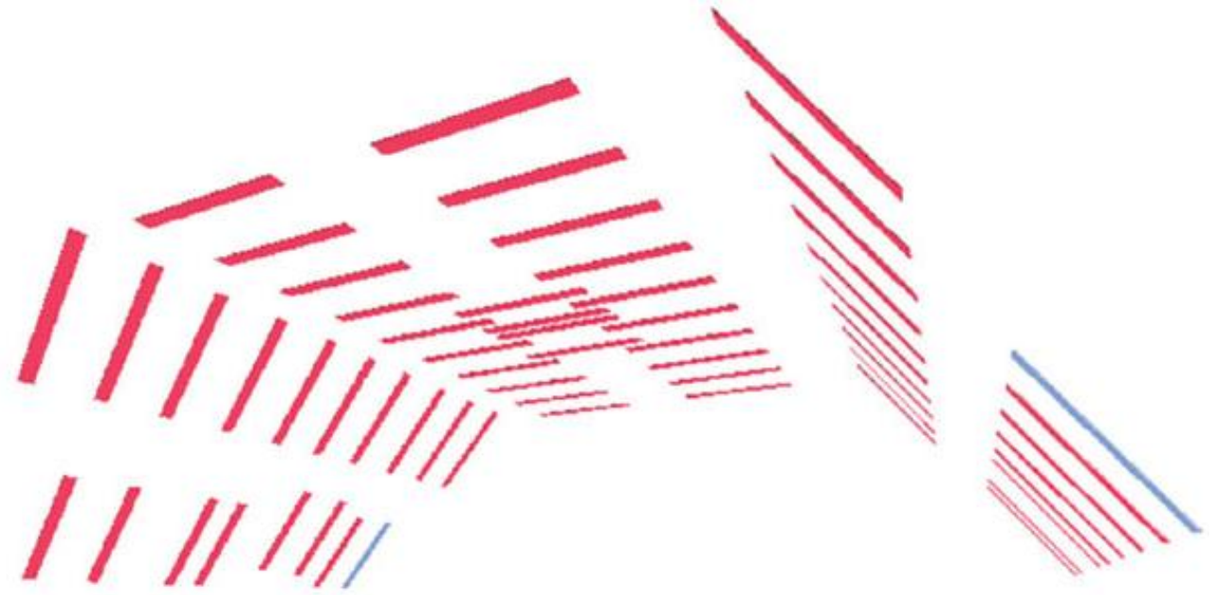
- **HEP**
  High Energy Physics
  models
- **EAS**
  Extensive Air Shower
  models



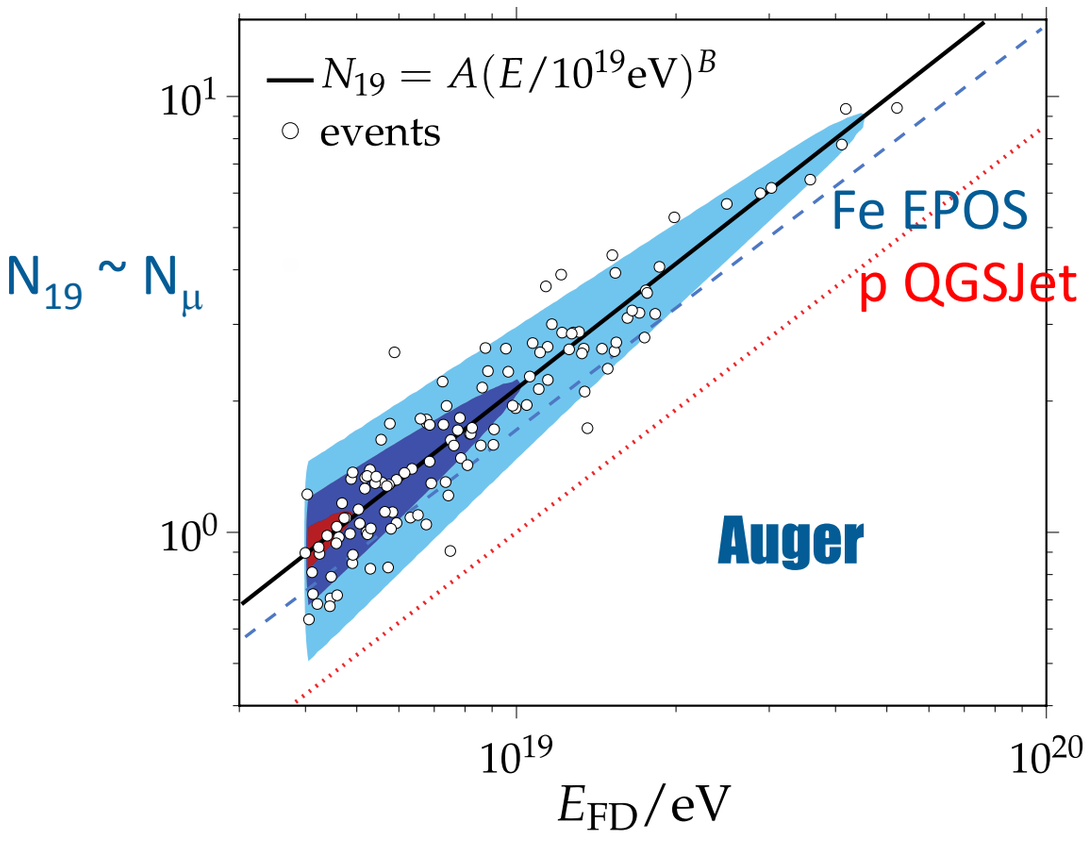
Another example

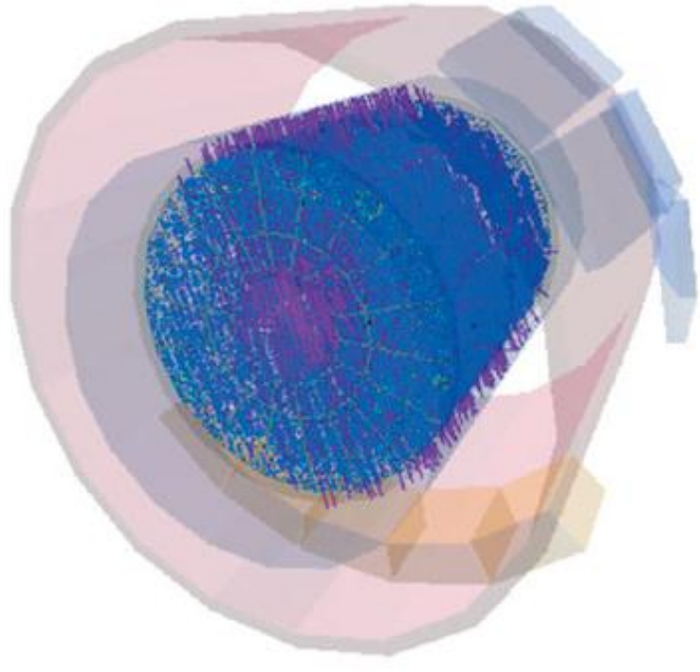
Extreme muon multiplicities

- High-multiplicity cosmic event in ALICE →
  - Density of ~18 muons/m^2 (within the TPC volume)



- Similar enigmas in underground experiments
- Muon numbers in EAS about 50-100% higher than MC predictions





- → Upgrade EAS experiments with muon counters

ApPEC
ASPERA Astroparticle Physics for Europe

Cosmic Rays and LHC: Summary

- Cooperation of particle- and CR-physicists has been intensified over the last years.
- This is extremely useful for understanding CR nature; accelerator data already helped improving shower models.
- Tools of CR community may also help better understanding HE particle interactions: bulk LHC data are well described by EAS models, sometimes even better than by HEP models
- Need common approach to understand muons in CR.
- NA61/SHINE (SPS Heavy Ion and Neutrino Experiment): important input data for cosmic ray and neutrino experiments. Submitted paper #21 for plans beyond the approved program.

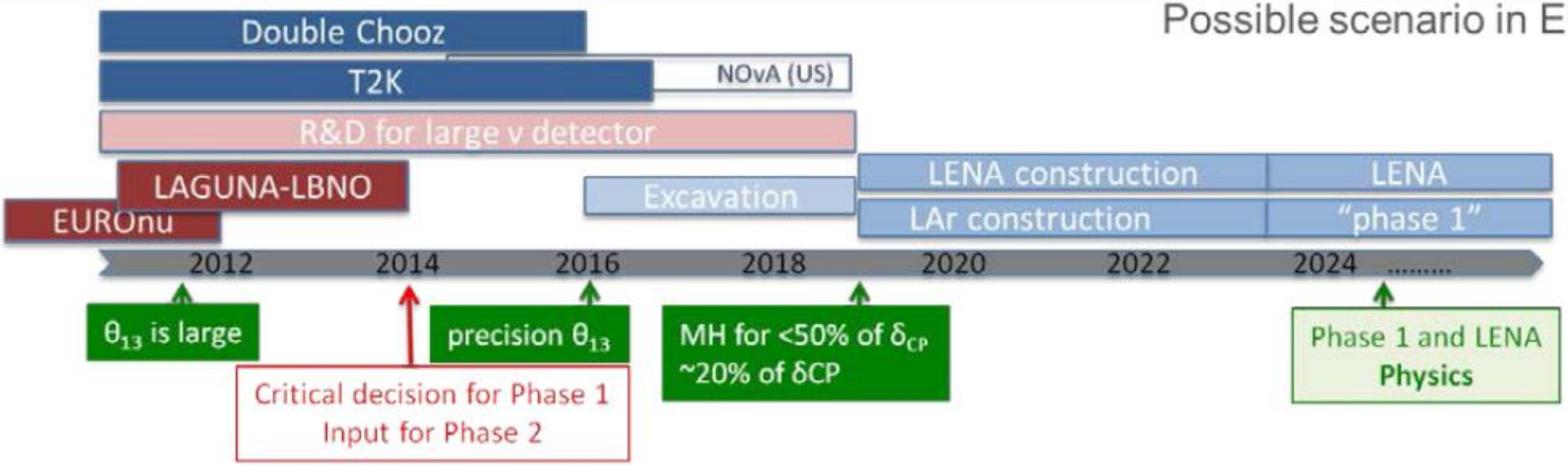
- **Establishing an „Astroparticle Physics Forum“ at CERN would intensify co-operation and synergies.**

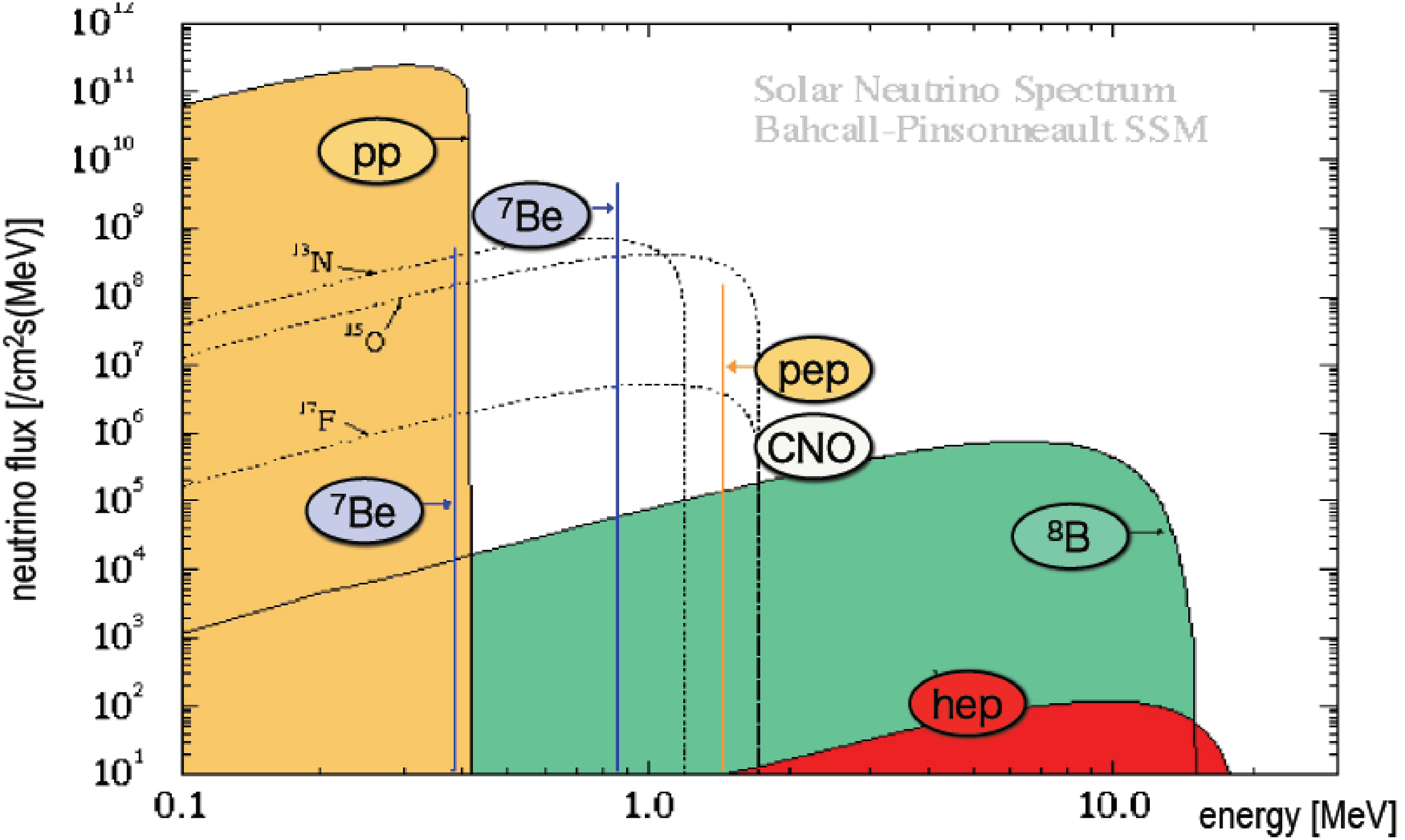
Summary

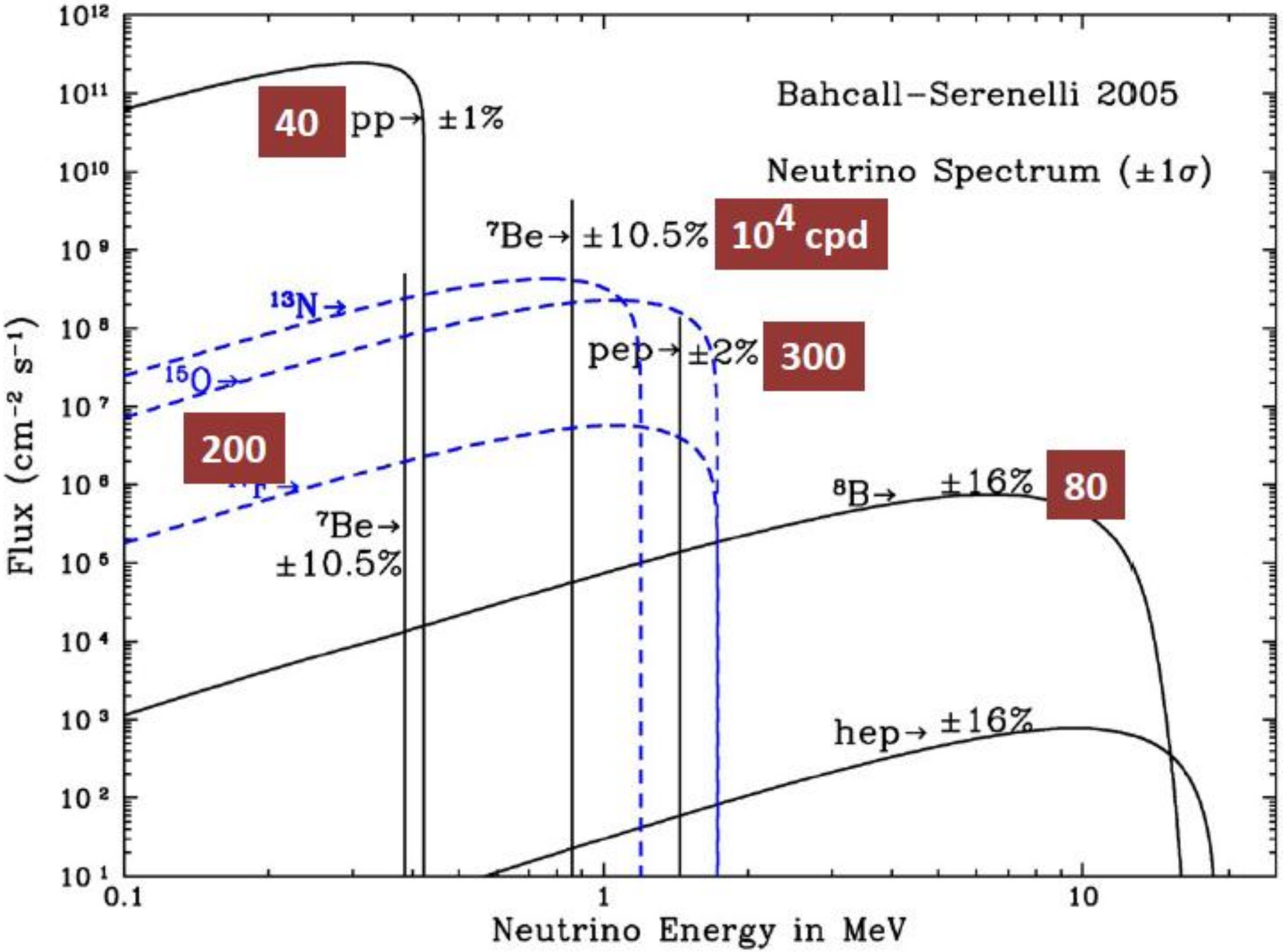
- **Dark Matter:**
  - close synergy "direct – indirect – LHC"
  - Direct measurements: → … → DARWIN, EURECA
- **Double Beta Decay**
  - Cover inverted hierarchy region
  - Phased approach to one-ton detector(s)
- **Nu astronomy and p-decay**
  - Combines fundamental discovery physics and precision physics
  - Combines astro- and particle physics
- **High energy Universe**
  - LHC ↔ air showers
  - Indirect dark matter search
  - Test of fundamental principles

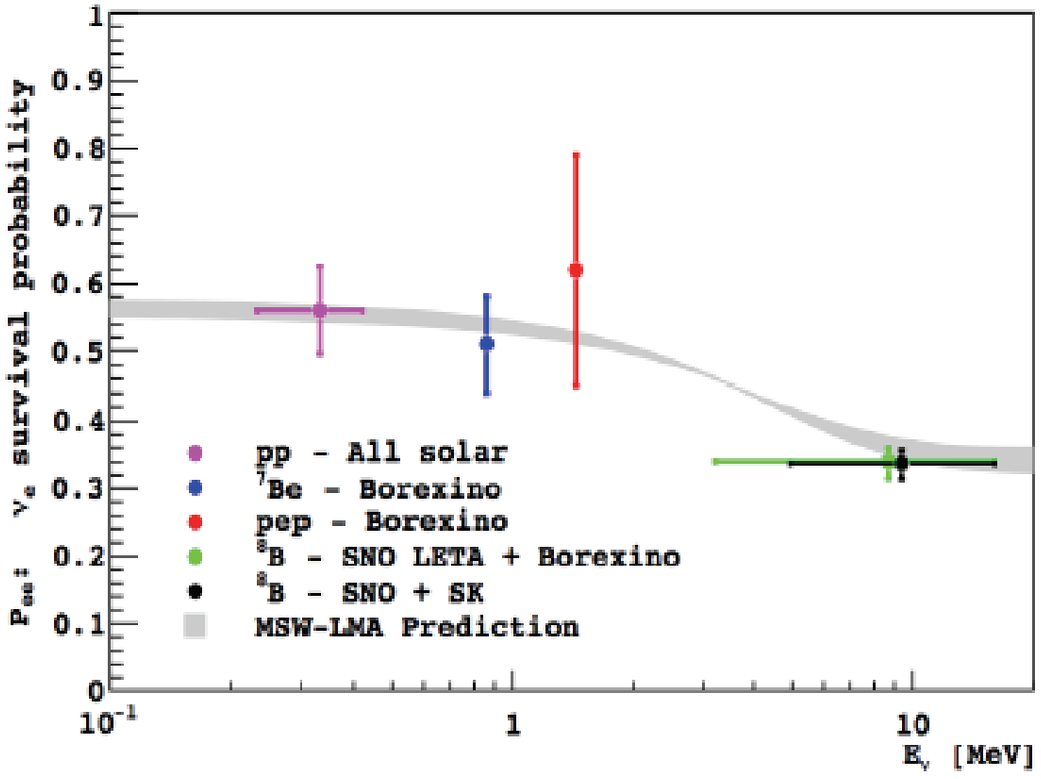
- **Need global approach** (the higher the cost, the more urgent)
- **Install "Astroparticle Physics Forum" at CERN**
- **Closer cooperation between CERN and ApPEC**

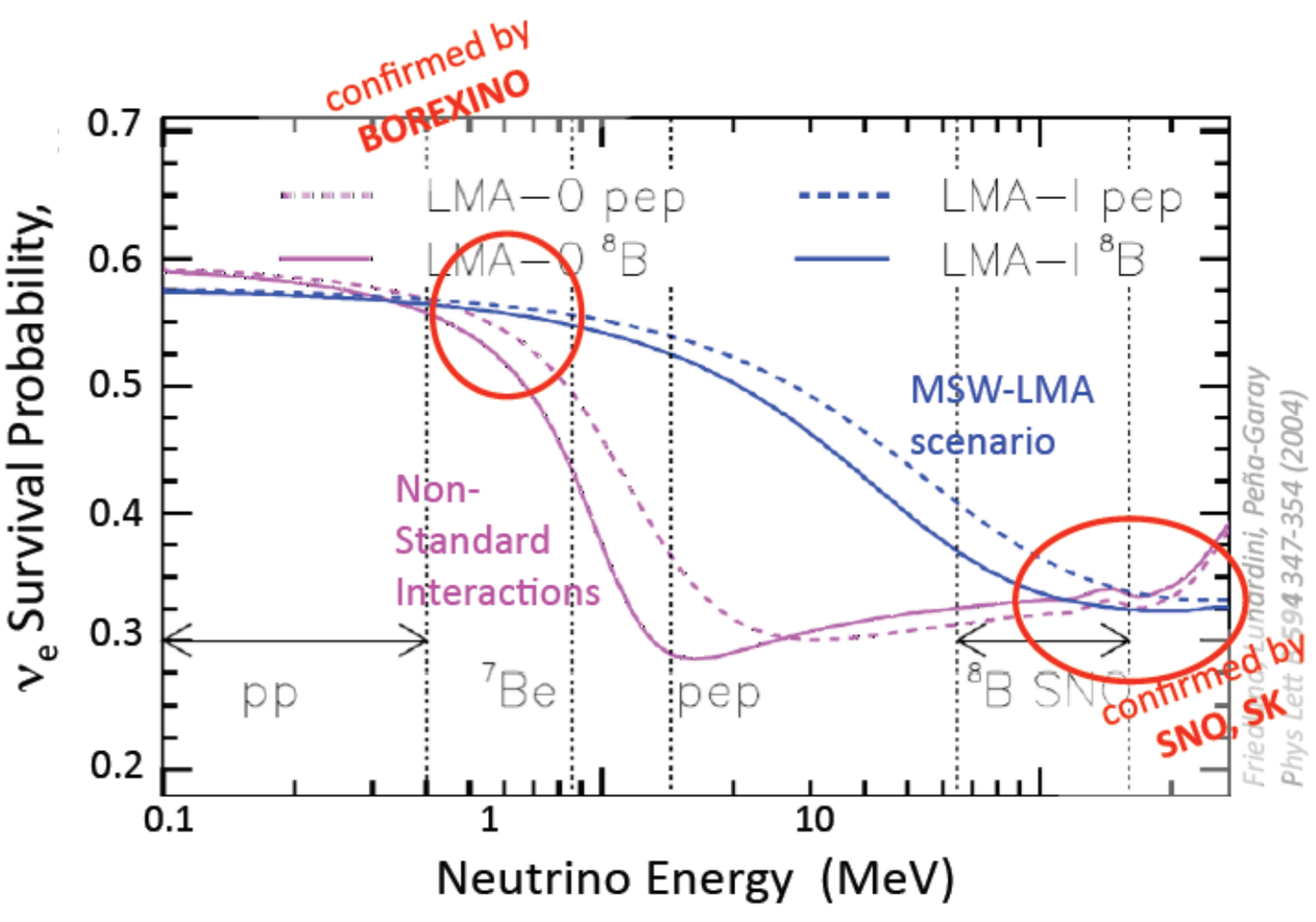
Possible scenario in EU




Solar Neutrino Spectrum
Bahcall-Pinsonneault SSM
pp
7Be
13N
15O
17F
pep
CNO
8B
hep
7Be
neutrino flux [/cm2s(MeV)]
energy [MeV]
0.1
1.0
10.0

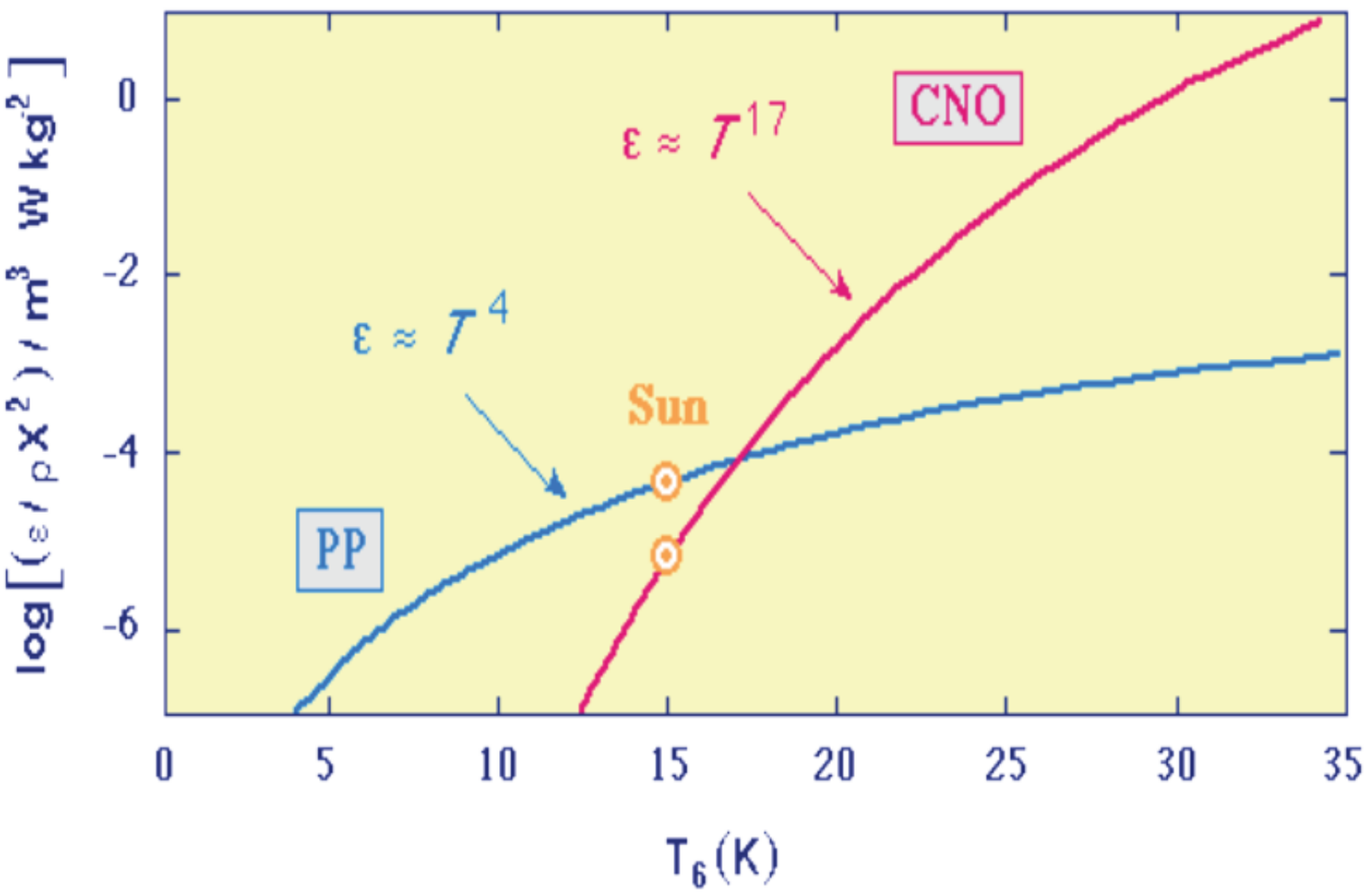

Bahcall–Serenelli 2005
Neutrino Spectrum (±1σ)
40
pp → ±1%
7Be → ±10.5%
10^4 cpd
13N →
15O →
pep → ±2%
300
200
8B → ±16%
80
7Be →
±10.5%
hep → ±16%
Flux (cm^-2 s^-1)
Neutrino Energy in MeV
0.1
1
10

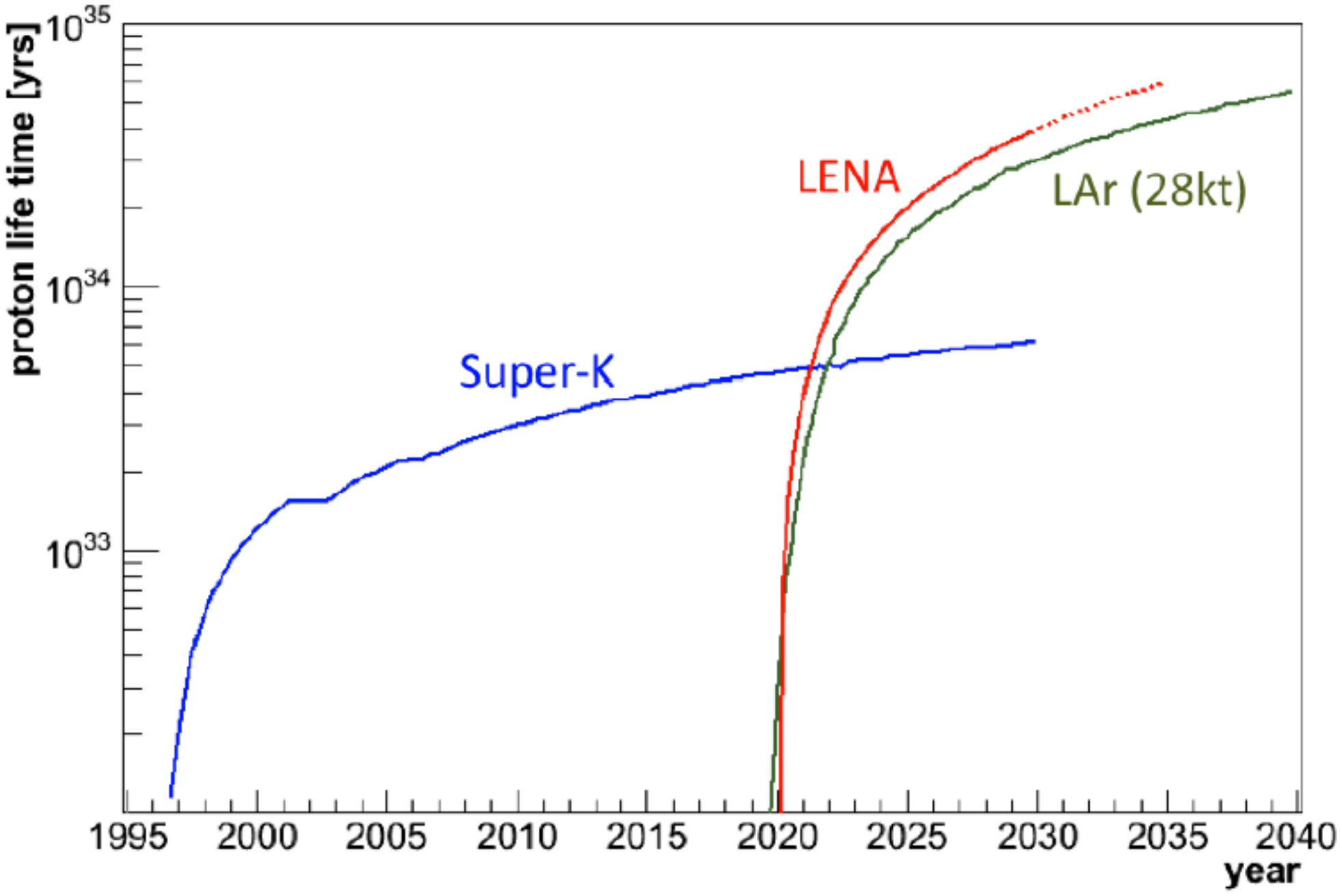

P_{ee}: ν_e survival probability
pp - All solar
^{7}Be - Borexino
pep - Borexino
^{8}B - SNO LETA + Borexino
^{8}B - SNO + SK
MSW-LMA Prediction
E_ν [MeV]


confirmed by BOREXINO
LMA–O pep
LMA–O ^{8}B
LMA–I pep
LMA–I ^{8}B
MSW-LMA scenario
Non-Standard Interactions
pp
^{7}Be
pep
^{8}B SNO
confirmed by SNO, SK
ν_e Survival Probability,
Neutrino Energy (MeV)
Friedland, Lunardini, Peña-Garay
Phys Lett B 594 347-354 (2004)

Astrophysics

- contribution of CNO cycle to solar fusion rate
- metallicity of solar core
- presence of time variations in solar neutrino flux (10^{-3} level)
  → helioseismic g-modes …




proton life time [yrs]
10^{35}
10^{34}
10^{33}
LENA
LAr (28kt)
Super-K
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
year

Test of sterile neutrino scenarios

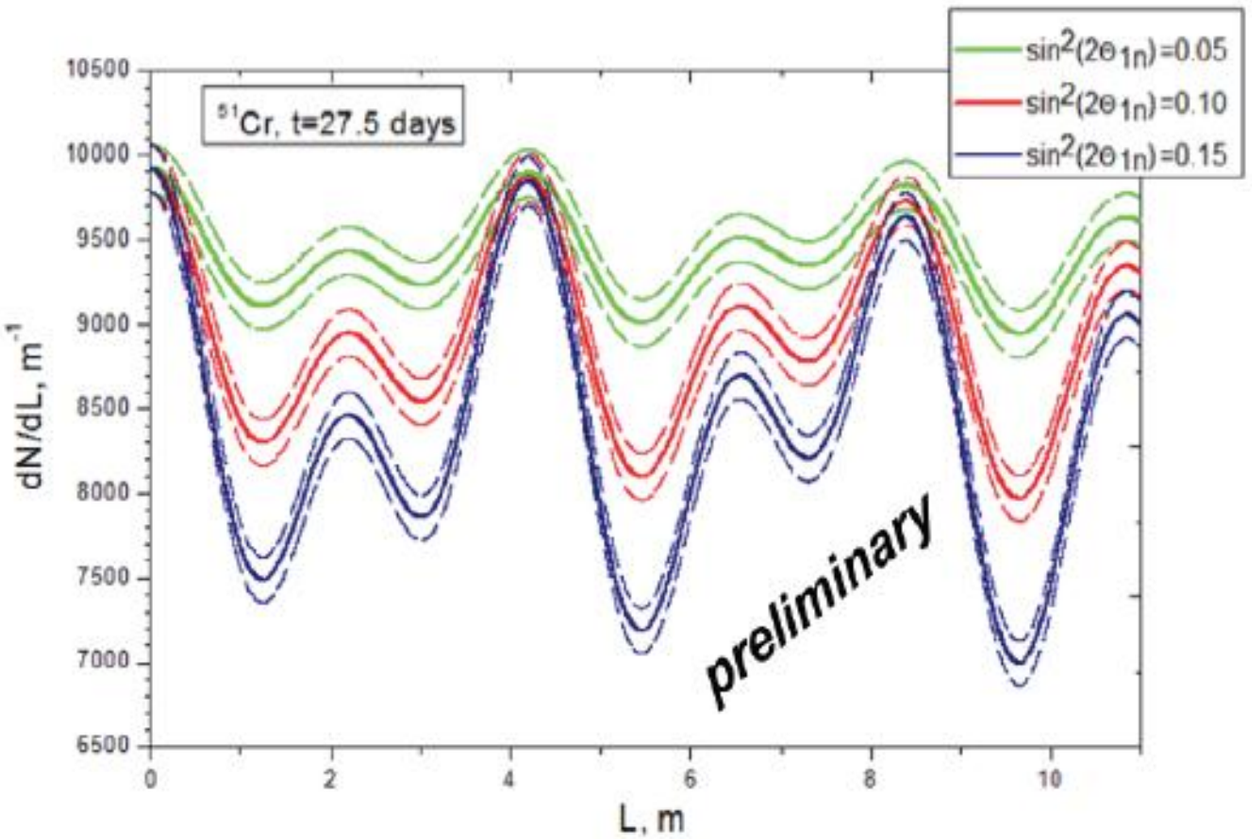
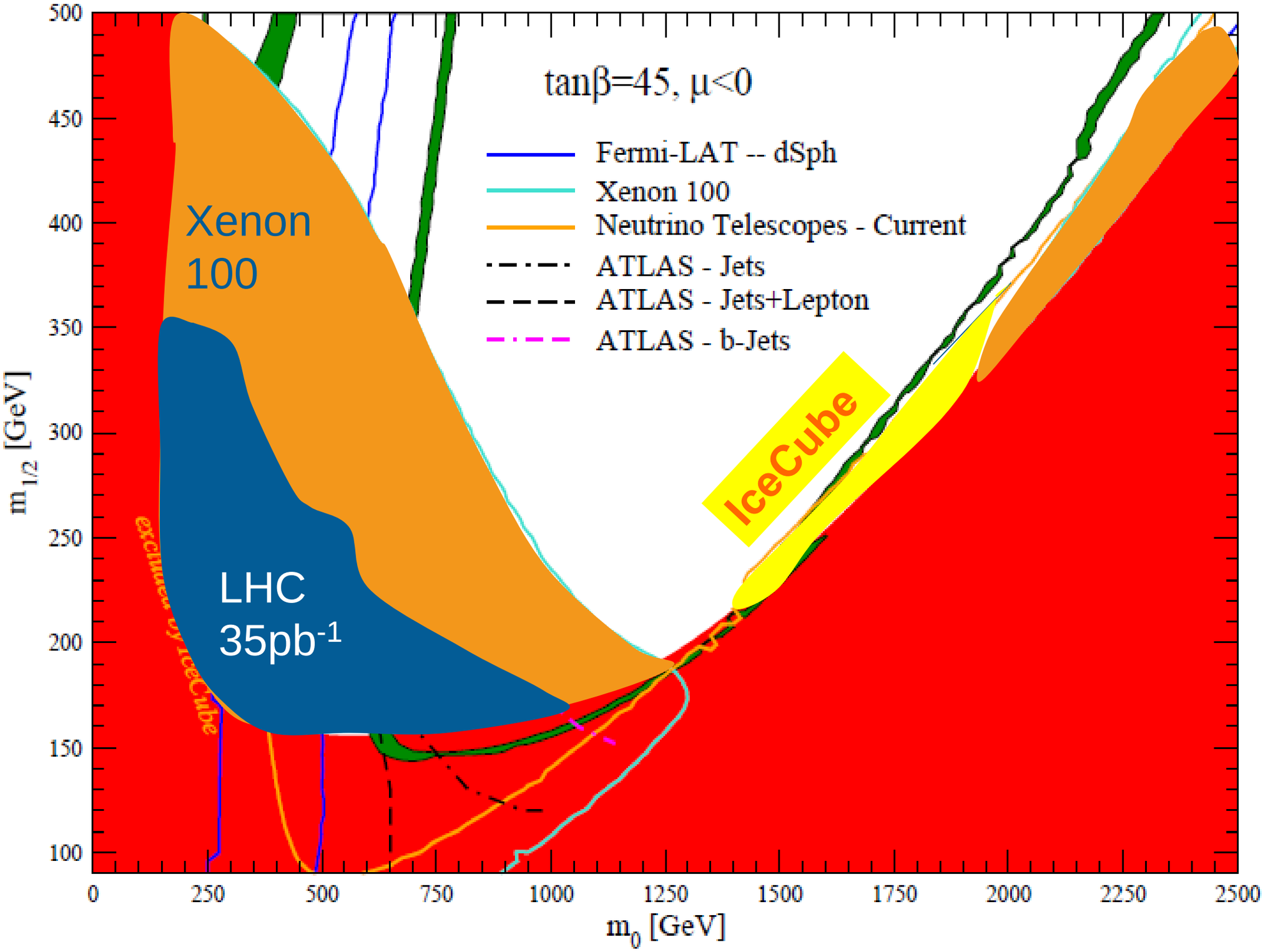
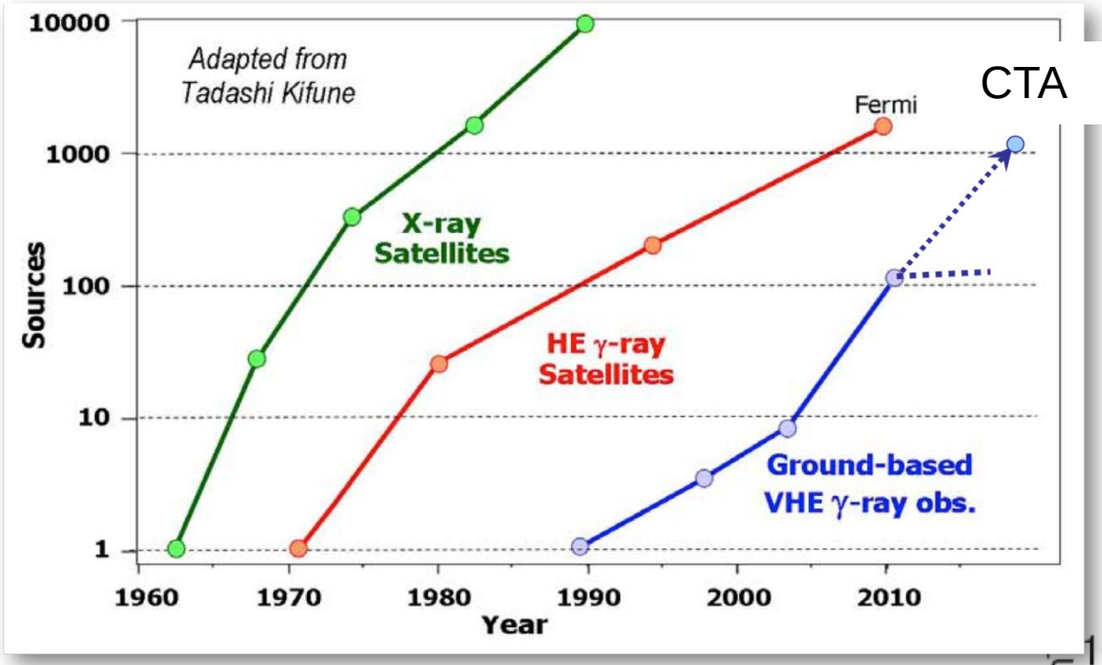


Fig. 8. Oscillometry curves for the case of three active and two sterile neutrinos in the (3+2) scenario with mass parameters proposed in [6]. In the figure top (green), middle (red) and bottom (blue) curves correspond to $sin^2(2\theta_{1n}) = 0.05; 0.10; 0.15$, respectively, with n=4, 5. The dashed lines indicate the statistical uncertainties (1σ). Input parameters are $(T_e)_{th}$ = 200 keV, R_0 = 11 m, exposure - 27.5 days, ^{51}Cr-source intensity – 5 MCi. The background from solar neutrinos is taken from the BOREXINO experiment [26] as 0.5 events/day·t.

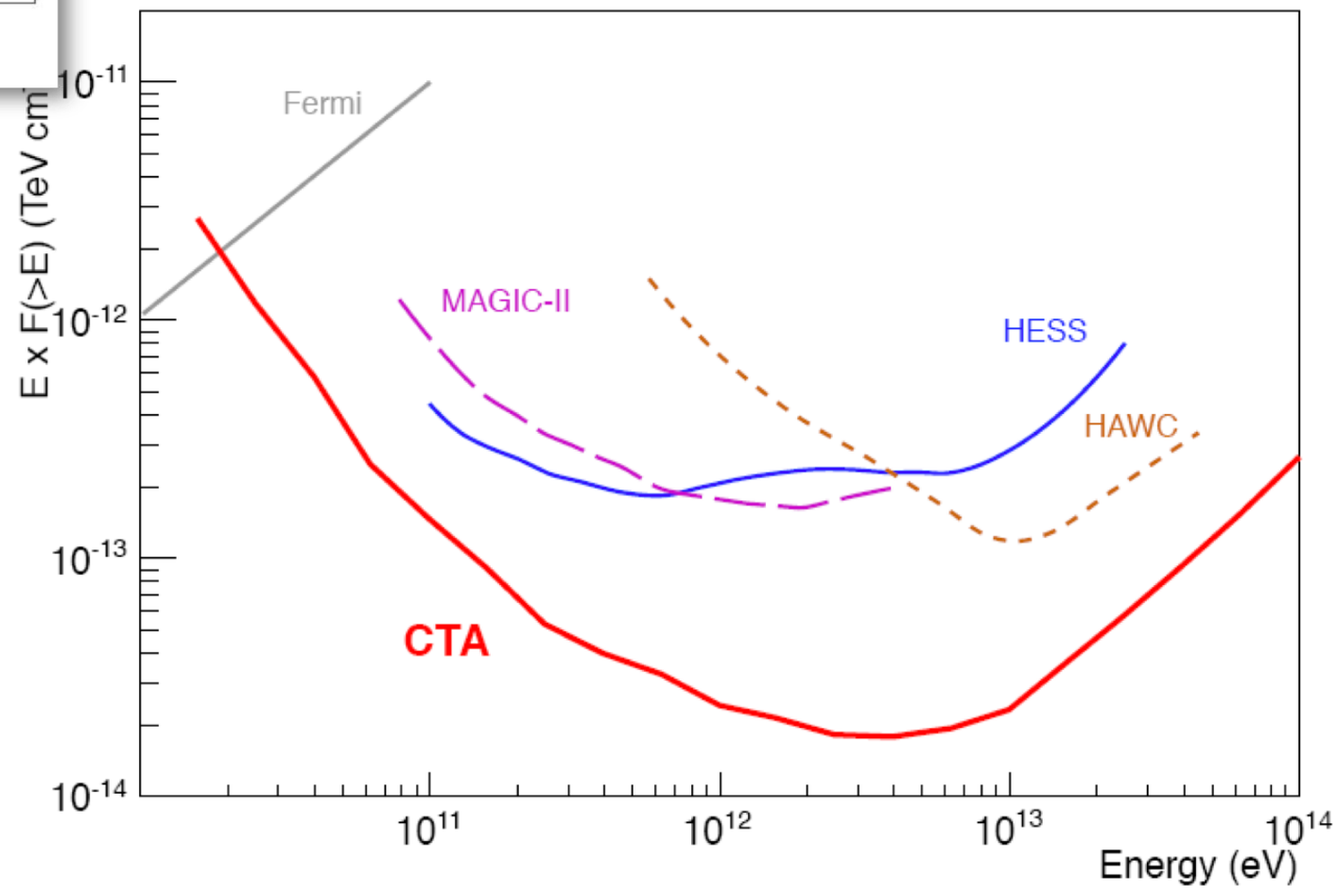
	Old: (GS98)		New: (AGSS09)		Best Measurements	
	Flux $cm^{-2}\ s^{-1}$	Error %	Flux $cm^{-2}\ s^{-1}$	Error %	Flux $cm^{-2}\ s^{-1}$	Error %
pp	5.98×10^{10}	± 0.6	6.03×10^{10}	± 0.6	6.05×10^{10}	$+0.3/-1.1$
pep	1.44×10^{8}	± 1.1	1.47×10^{8}	± 1.2	1.46×10^{8}	$+1/-1.4$
hep	8.04×10^{3}	± 30	8.31×10^{3}	± 30	18×10^{3}	$+40/-50$
^{7}Be	5.00×10^{9}	± 7	4.56×10^{9}	± 7	4.82×10^{9}	$+5/-4$
^{8}B	5.58×10^{6}	± 14	4.59×10^{6}	± 14	5.00×10^{6}	± 3
^{13}N	2.96×10^{8}	± 14	2.17×10^{8}	± 14	$< 6.7 \times 10^{8}$	
^{15}O	2.23×10^{8}	± 14	1.56×10^{8}	± 14	$< 3.2 \times 10^{8}$	

- Directly measured 7-Be (Borexino) and 8-B (SNO) fluxes are halfway between
- CN fluxes depend linearly on abundances, measurements needed

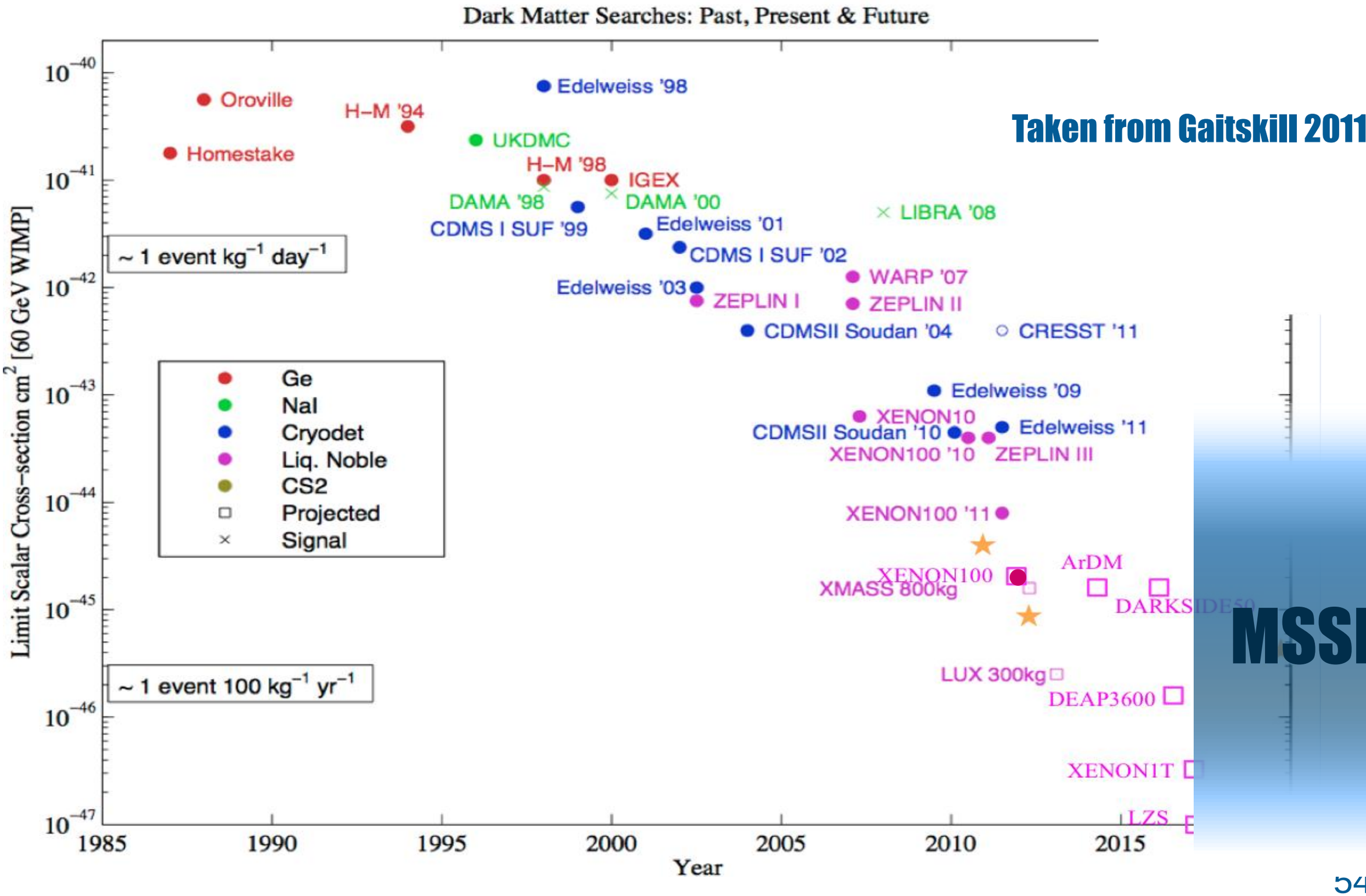

tanβ=45, μ<0
Fermi-LAT -- dSph
Xenon 100
Neutrino Telescopes - Current
ATLAS - Jets
ATLAS - Jets+Lepton
ATLAS - b-Jets
Xenon 100
LHC 35pb-1
IceCube
excluded by IceCube
m1/2 [GeV]
m0 [GeV]
500
450
400
350
300
250
200
150
100
0
250
500
750
1000
1250
1500
1750
2000
2250
2500



The future in
VHE gamma ray
astronomy:



The Perspective



Taken from Gaitskill 2011